Mobile Radio Network Management in the Context of Realistic Heterogeneous Scenarios

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Sören Hahn, M.Sc.

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1. Referent:	Prof. Dr.-Ing. Thomas Kürner
2. Referent:	Prof. Dr. Hans van den Berg
Vorsitzender:	Prof. Dr.-Ing. Ulrich Reimers

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“After climbing a great hill, one finds that there are many more hills to climb.”

— Nelson Mandela

Vorwort

Diese Arbeit ist komplett während meiner Zeit am Institut für Nachrichtentechnik der Technischen Universität Braunschweig entstanden. Sie basiert zu einem sehr großen Teil auf Forschungsergebnissen, die im Rahmen des europäischen SEMAFOUR-Projektes erarbeitet wurden. Obwohl eine Promotion dem Nachweis der Befähigung zu vertiefter selbstständiger wissenschaftlicher Arbeit auf einem ausgewiesenen Fachgebiet dienen soll, wäre diese Dissertation jedoch ohne die Unterstützung zahlreicher Menschen so nicht möglich gewesen. Deshalb möchte ich an dieser Stelle genau diesen Personen meinen Dank aussprechen.

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Braunschweig, im September 2017 Sören Hahn

Abstract

Every generation of mobile radio communication standards leads to a new level of complexity in the cellular systems. Moreover, due to the ever-increasing data traffic demands of mobile users as well as declining revenues in recent years, the operators of such networks have to deal with all those network administration difficulties in the most efficient manner. One promising approach that shall relieve the operator from time-consuming manual tasks is to use so-called Self-Organising Network (SON) functionalities. SON functions monitor the performance of the network and change the (radio) parameters accordingly, based on internal algorithms that focus on dedicated optimisation goals.

This work investigates whether SON functions can be used to enforce Key Performance Indicator (KPI) targets demanded by the operators. Therefore, the impact of SON on the network manageability and performance is studied by using SON functions that consider multiple technologies (i.e. LTE and WLAN) and different cell layers (macro and small cells). The evaluations are based on sophisticated system-level simulations that rely on an in-house developed platform called "SiMoNe" (Simulator for Mobile Networks). Moreover, the foundations of the scenarios used are realistically planned mobile networks on the one hand, and advanced mobility models with a particular emphasis on realistic movements and behaviours, on the other hand.

As a preparatory step, the newly introduced mobility models are investigated regarding the handover performance. The results show that the behaviour and nature of the movements have a profound impact on the overall network performance. After that, three well-known SON functions are tested that operate in the domain of self-optimisation. This is done by varying SON algorithm parameterisation values in three distinct network environments. The insights gained into the behaviour of the SON functions are then used to manage a complex heterogeneous cellular network by setting appropriate SON parametrisation values that alter the behaviour of SON functions accordingly. By that, the formulated KPI goals can be achieved. However, the evaluations show that the implementations of the objectives are only doable to some extent in realistic settings due to the compound and inhomogeneous nature of the network scenarios.

Kurzfassung

Jede neue Mobilfunk-Generation sorgt dafür, dass die Komplexität in den Netzen zunimmt. Außerdem führt die immer weiter steigende Nachfrage nach mobilem Datenverkehr sowie sinkende Einnahmen dazu, dass die Betreiber solcher Netze mit administrativen Aufgaben in möglichst effizienter Weise umgehen müssen. Eine Möglichkeit stellen sogenannte Selbst-Organisierende Netze (engl. Self-Organising Network (SON)) dar, um den Betreiber von zeitaufwendigen manuellen Arbeiten zu befreien. SON Funktionen überwachen Kenngrößen im Netz und ändern, je nach Zielfunktion des Algorithmus, entsprechende (Radio-)Parameter im Netz.

Diese Dissertation untersucht, ob SON Funktionen geeignet sind um ein Mobilfunknetz zu steuern und somit vorgegebene Zielvorgaben der Netzbetreiber umzusetzen. Die verwendeten SON Funktionen arbeiten hierbei mit unterschiedlichen Technologien (z.B. LTE und WLAN) und auf mehreren Zellschichten (Makro- bis Femtozellen). Als Simulationsumgebung wird auf die leistungsfähige Plattform "SiMoNe" (engl. Simulator for Mobile Networks) zurückgegriffen. Die Simulationsgrundlagen bilden einerseits realistisch geplante Mobilfunknetze und anderseits fortschrittliche Mobilitätsmodelle, wobei eine besondere Betonung auf die realistische Umsetzung von Bewegung und Verhalten der Nutzer gelegt wird.

In einem vorbereitenden Schritt werden neuartige Mobilitätsmodelle auf ihr Handover-Verhalten untersucht. Die Ergebnisse zeigen hierbei, dass das Verhalten und die Bewegung einen entscheidenden Einfluss auf die Netzperformance haben können. Im Anschluss werden drei bekannte SON Funktionen in drei unterschiedlichen Netzumgebungen getestet. Dies geschieht durch eine Variation der Parameterwerte der SON Algorithmen, welche das Verhalten der Funktionen verändern und somit auch die Netzperformances entscheidend beeinflussen kann. Die über das Verhalten der SON Funktionen gesammelten Erkenntnisse werden letztendlich genutzt, um Zielvorgaben an ein komplexes heterogenes Mobilfunknetzwerk zu realisieren. Die Auswertungen zeigen, dass dies nur in einem gewissen Maße geschehen kann. Die hohe Komplexität und die inhomogene Topologie der Netze beeinträchtigen eine zielgenaue Veränderung der Netzperformance entscheidend.

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Abbreviations

2G	2nd Generation (GSM, GPRS, EDGE)
3G	3rd Generation (UMTS, HSPA)
3GPP	3rd Generation Partnership Project
4G	4th Generation (LTE, LTE-A, LTE-U)
5G	5th Generation
10X10	$10\,\mathrm{km} \times 10\,\mathrm{km}$ – Reference and Evaluation Scenario
AP	Access Point
BSM	Best Server Map
BSS	Basic Service Set
CAP	Cell Assignment Probability
CAPEX	CAPital EXpenditures
CBR	Constant Bit Rate
CIO	Cell Individual Offset
CM	Configuration Management
COST	European COoperation in Science and Technology
CSMA	Carrier Sense Multiple Access
ECA	Event-Condition-Action
eNB	evolved Node B
EPC	Evolved Packet Core
EPS	Evolved Packet System
EUTRAN	Evolved UMTS Terrestrial Radio Access Network
ESS	Extended Service Set
ETSI	European Telecommunications Standards Institute
FM	Fault Management
FP7	Seventh Framework Programme
FTP	File Transfer Protocol
GSM	Global System for Mobile Communications

HO	Handover
HOF	Handover Failure
HOFR	Handover Failure Ratio
HOSR	Handover Success Ratio
HP	Handover Performance
HPI	Handover Performance Indicator
HSS	Home Subscriber Server
HYS	Hysteresis
IEEE	Institute of Electrical and Electronics Engineers
IoT	Internet of Things
IP	Internet Protocol
KDE	Kernel Density Estimation
KPI	Key Performance Indicator
KS-Test	Kolmogorov-Smirnov Test
LAN	Local Area Network
LB	Load Balancing
LTE	Long Term Evolution
MCS	Modulation and Coding Scheme
MM	Mobility Model
MME	Mobility Management Entity
MNO	Mobile Network Operator
NEM	Network Empowerment Mechanism
NGMN	Next Generation Mobile Networks
OFDM	Orthogonal Frequency Division Multiplexing
OPEX	OPerational EXpenditures
OSM	OpenStreetMap
PBSM	Policy-Based SON Management
PDF	Probability Density Function
PDN-GW	Public Data Network Gateway
PM	Performance Management
PP	Ping-Pong Handover
PPHOR	Ping-Pong Handover Ratio
PRB	Physical Resource Block
PSON	Period of SON execution

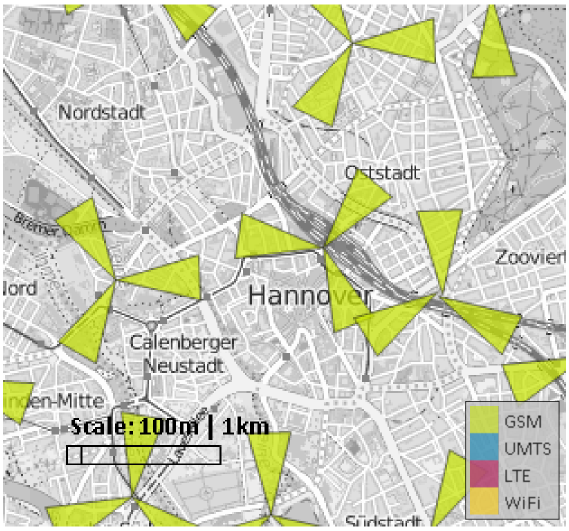
QoE	Quality of Experience
QoS	Quality of Service
RAT	Radio Access Technology
RH	Rural location and High-speed mobility mix
RLF	Radio-Link-Failure
RLFR	Radio-Link-Failure Ratio
RN	Rural location and Normal mobility mix
RO	Robustness Optimisation
RSS	Received Signal Strength
SCP	SON Function Configuration Parameter
SCV	SON Function Configuration Value
SEMAFOUR	SElf-MAnagement FOr Unified Heterogeneous Radio Access Networks
SeNB	Source evolved Node B
SFPM	SON Function Performance Model
S-GW	Serving Gateway
SiMoNe	Simulator for Mobile Networks
SINR	Signal-to-Interference plus Noise Ratio
SMA	Simple Moving Average
SOCRATES	Self-Optimisation and self-ConfiguRATion in wirelEss networkS
SOM	SON Objective Manager
SON	Self-Organising Network
SQL	Structured Query Language
SUMO	Simulator of Urban Mobility
TeNB	Target evolved Node B
TP	Throughput
TS	Traffic Steering
TTT	Time-To-Trigger
UE	User Equipment
UMF	Unified Management Framework
UMTS	Universal Mobile Telecommunications System
UN	Urban location and Normal mobility mix
UU	Unsatisfied User
WiFi	Wireless Fidelity
WLAN	Wireless Local Area Network

Chapter 1

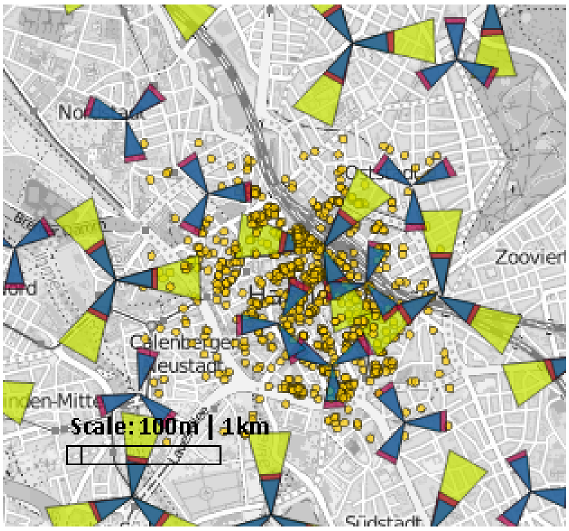
Introduction

Mobile radio networks have evolved drastically over the last decades. Since the introduction of the Global System for Mobile Communications (GSM), the complexity of mobile networks has increased with each Radio Access Technology (RAT) that was introduced and added over the years. Figure 1.1[1] gives a visual and placative example for that. It shows a so-called single-layer, single-RAT topology on the left. This was a typical network topology in the early nineties of the last century in almost any given city in Germany. This single-layer GSM network, which is also referred to as the 2nd Generation (GSM, GPRS, EDGE) (2G) of mobile communications, operating at e.g. 900 MHz, is providing enough coverage *and* capacity for most of the mobile system. Figure 1.1b depicts a much more complicated scenario, which shows multiple RATs operating at various frequencies, i.e. the network layers. Over the years, the Mobile Network Operators (MNOs) needed to add new RATs that provided a higher spectral efficiency to cope with the ever-increasing demand for more data traffic by users in the network. These upgrades included, for example, the Universal Mobile Telecommunications System (UMTS) around the turn of the millennium (from now on referred to as the 3rd Generation (UMTS, HSPA) (3G)). Later on, the 3rd Generation Partnership Project (3GPP) introduced Long Term Evolution (LTE) to address drawbacks identified in UMTS (i.e. the 4th Generation (LTE, LTE-A, LTE-U) (4G)). Additionally, Wireless Local Area Network (WLAN) systems, standardised by the Institute of Electrical and Electronics Engineers (IEEE), are now also partly in the hand of the MNO (shown as yellow circles in Figure 1.1) [3GP17b]. With the 5th Generation (5G) on the horizon, it is safe to assume that the complexity of the system is about to increase even further.

[1] The frequencies are coded into the lengths of the sector markers (the triangles in Figure 1.1). A larger marker indicates a lower frequency and, hence, a potentially greater coverage due to better propagation characteristics



(a) Around 1990 in Germany: single-layer and single-RAT – one GSM layer operating at 900 MHz



(b) Around 2010 in Germany: multi-layer and multi-RAT – with GSM 900, UMTS 2100, LTE 1800 and WiFi 2400

Figure 1.1: Evolution of a mobile radio network over several decades

Moreover, mobile radio networks were initially meant to handle voice calls only, which was also the main design criterion for GSM. However, as already mentioned, the requirements of the users in the system become more and more data-driven. This is also observable by looking at Figure 1.2 [Bit15]. Here, the total revenue is shown – for voice (*red*) and data (*blue*) services in all mobile radio networks in Germany. Several trends are noticeable. First, the revenue of voice services is decreasing over the years, whereas data applications generate more and more revenue. Second, the study expected that the revenue coming from data services will overpass the voice revenue for the first time ever in 2015. All this requires the MNO to rethink the management and operation of its mobile network. To become more efficient, resilient and to reduce the OPerational EXpenditures (OPEX) as well as CAPital EXpenditures (CAPEX), new mechanisms have to be exploited that enable a flexible, reliable and sustainable network management and operation.

1.1 The Need to Alter the Performance of a Mobile Network

One way to reduce CAPEX is to utilise the existing resources, e.g. available spectrum or hardware used, in an efficient manner as long as possible. This in itself is a quite complex endeavour, due to the changing requirements coming from the (end-) users and

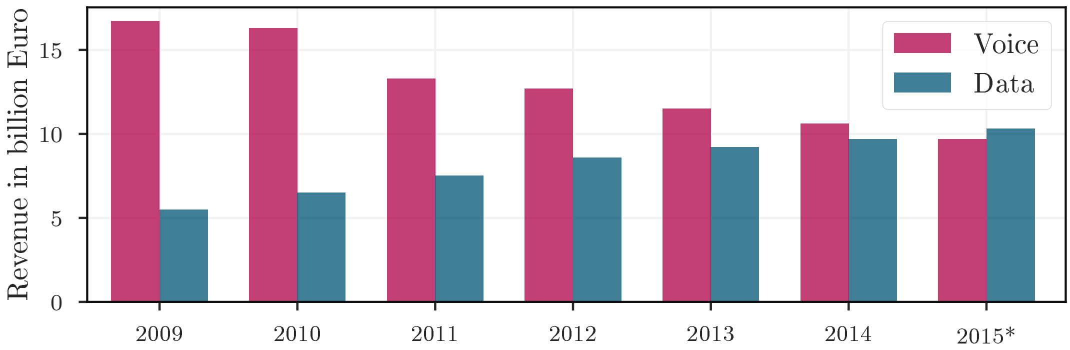


Figure 1.2: Total revenue of voice and data services in mobile radio networks in Germany from 2009 to 2015 [Bit15]

the complex network infrastructure. In light of the points just mentioned an MNO thus wants to formulate objectives to ensure a preferred system operation like the following:

- *Small WLAN cells in the inner city shall provide the highest data rates possible during the busy hour to ensure a high Quality of Experience (QoE) for our customers.*
- *GSM cells covering a motorway should have a low call drop ratio to provide the best Quality of Service (QoS) for voice calls.*
- *At night time, the UMTS and GSM cells have to save energy to reduce our OPEX. However, LTE cells have to remain untouched to ensure coverage.*

These three objective formulations already feature a couple of conditions. For example, multiple *RATs* are addressed (GSM, UMTS, LTE as well as WLAN), the focus lies on different *KPIs* (throughput, call drop ratio and energy savings), various *locations* or *environments* are mentioned (inner city or motorway) and finally, the *time of day* shall be considered as well (busy hour or night time). The question now is, how does an MNO has to adjust the underlying network configurations, so that the measured KPIs are in line with these (possibly changing) objectives? This identifies a so-called *manual gap* between the MNO and the underlying cellular network (as shown in Figure 1.3 as well as in [HSS12, pp. 39] and [RH12, pp. 28]). The MNO on top defines objectives that somehow have to be reflected in the system by adjusting (radio) parameters manually and appropriately. The system then has to report back whether the objectives (in terms of measured KPIs) are achievable or not. If the mobile network cannot fulfil these objectives, the MNO has to (manually) re-adjust the parameters

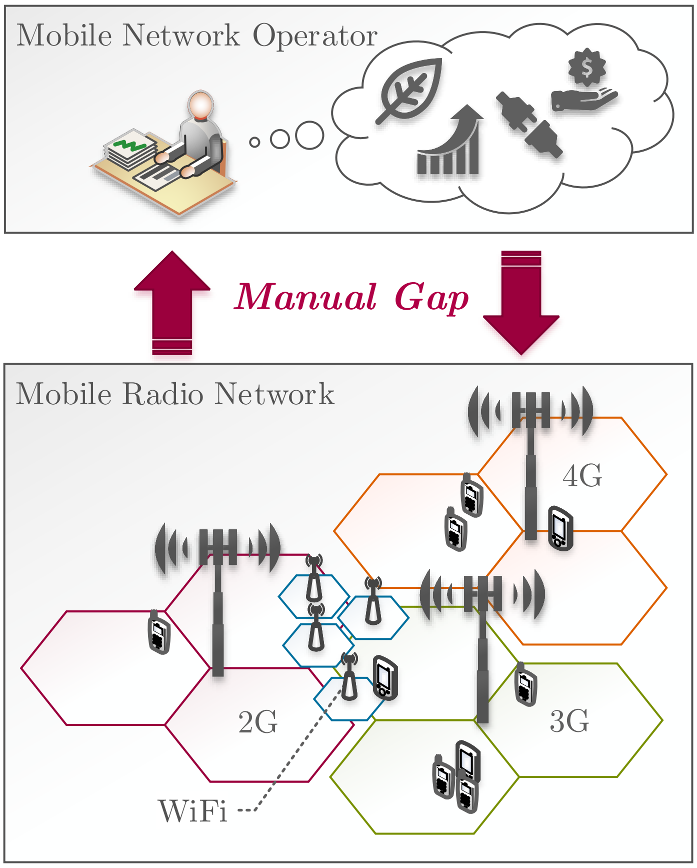


Figure 1.3: The manual gap – mobile network operator decisions in a complex cellular system

again (hence the *gap*) until the desired network performance is achieved, which usually leads to time-consuming and costly undertakings.

Thus, this thesis will introduce a *network management layer* that translates the objectives, coming from the MNO, and enforces changes in the mobile network configurations to attain the desired KPIs and to close this manual gap. Figure 1.4 shows this layer in red. The management layer will make use of so-called Self-Organising Network (SON) functionality (indicated by the added coloured arrow-loops in Figure 1.4) to execute the operator objectives. SON has been an active research topic for several years now and has gained in importance with the introduction of Release 8 of the 3GPP [3GP08]. Nowadays, several SON algorithms are available – each usually focusing on one dedicated (optimisation) task by continuously measuring and executing (radio) parameter changes in the network. Such SON functions, which are used to alter KPIs in the network, are steerable as well by modifying (SON related) configuration parameters. By that, the behaviour of the algorithm changes and, thus, the impact on

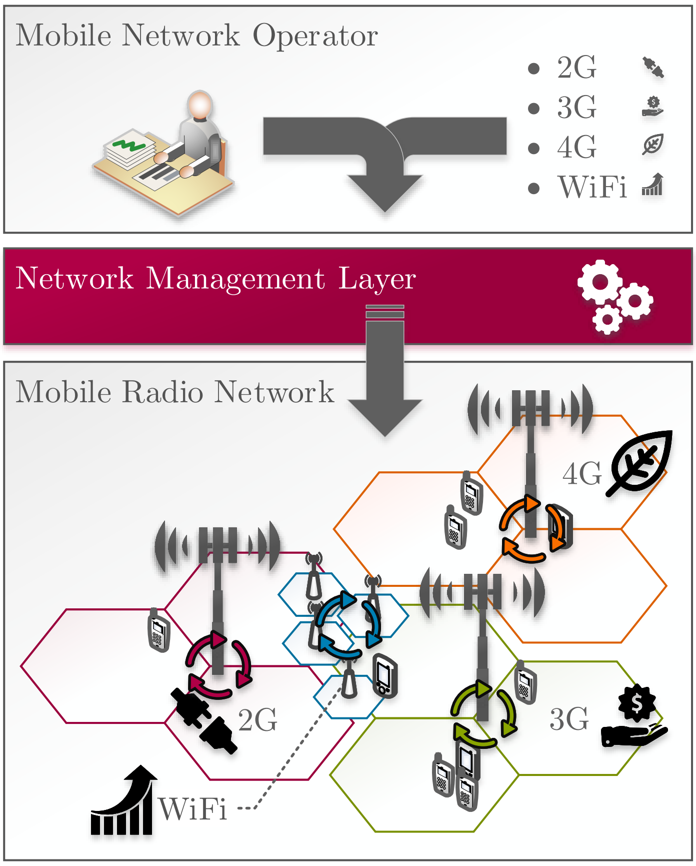


Figure 1.4: The network management layer – added functionality to close the manual gap

the overall network performance, too. However, how to *use* SON functions and how to *adapt* the underlying algorithms accordingly are part of the investigations of this thesis. This is done by using an in-house developed simulation platform as well as realistic network scenarios to conduct sophisticated system-level simulations to evaluate the impact of SON on a complex, large-scale radio network.

Table 1.1: Considered multi-layer and multi-RAT SON functions in this thesis and the contemplated areas of deployment regarding the technology and cell size of the network element

		Layer	
		large	*small*
RAT	*LTE*	● ■ ▲	● ■
	WiFi		▲

● LTE Load Balancing

■ LTE Robustness Optimisation

▲ LTE/WiFi Traffic Steering

As Table 1.1 shows, this thesis considers three well-known SON functions that work on different layers and in two RATs. With that, the needs of an MNO, which has to operate a multi-layer and multi-RAT network, are addressable in a profound way.

1.2 Approach of the Work

Based on the needs explained here to adopt the performance of a modern mobile radio network so that it is in line with the operator vision, several requirements emerge. The altering of the system performance is executable with the aid of SON functionality. Furthermore, the evaluation relies on mature and realistic network simulations only. This approach is the only possibility to test SON functions before deploying them in the live network and retrieving meaningful information about the performance thereof. For that, the structure of this work is as shown in Figure 1.5: At first, chapter 2 provides the necessary fundamentals for this thesis. It presents the required details regarding the modelling and simulation of mobile radio networks. After that, the SON functions and the KPIs herein used are explained and defined. The chapter finishes with an overview of the state of the art and open issues about network management as well as mobility modelling.

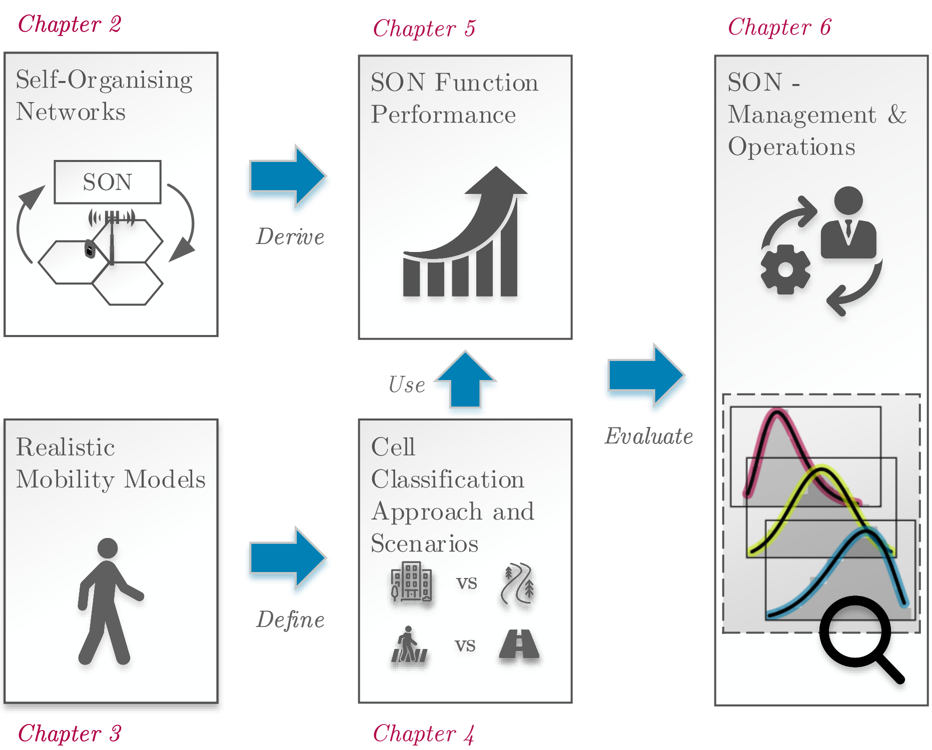


Figure 1.5: Methodology and structure of the thesis

Building upon the previous descriptions of the realistic network scenarios, chapter 3 introduces advanced mobility models. In a preparatory step, first evaluations are carried out that feature the impact of realistic movements on Handover Performance (HP) metrics. After that, chapter 4 explains the applied simulation scenarios, including the aforementioned advanced mobility models as well. Additionally, the chapter describes a cell classification approach that represents an integral part of this thesis. Besides the SON functions, the classification of cells is a key enabler of the implemented network management framework. The defined simulation scenarios are then used to analyse the different SON functions in detail in chapter 5 by varying the SON function control parameters. Finally, with the cell classification approach (chapter 4) and the insights gained into the SON function behaviours (chapter 5), chapter 6 investigates the altering of the network performance and the impact of multiple SON functions on the KPIs. A summary and an outlook are given in chapter 7.

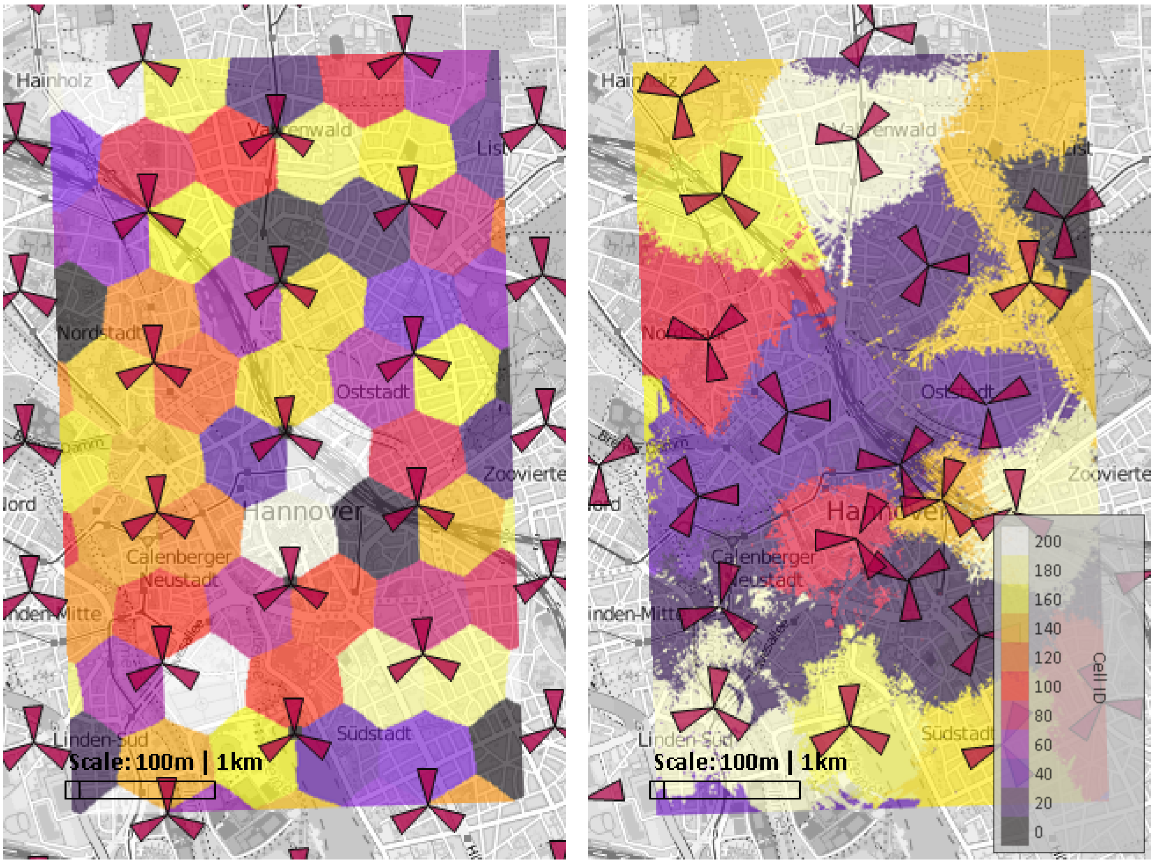
Chapter 2

Fundamentals

Sophisticated scenarios are necessary to describe the varieties and disparities of a modern, large-scale, and inhomogeneous mobile radio network. For that, section 2.1 describes the level of detail with respect to the system modelling, topologies and the simulation tools used to evaluate multi-layer, multi-RAT scenarios. As mentioned in chapter 1, this thesis uses three well-known SON functions. Brief descriptions can be found in section 2.2. Finally, section 2.3 introduces four KPIs to evaluate the performance of mobile networks. The KPIs are assessed later on by simulating multiple SON functions and evaluating (self-organising) network management concepts.

2.1 Realistic Network Scenarios

The need for realistic network scenarios comes mainly from the already mentioned and ever-increasing complexity of modern mobile networks. Scenario descriptions, coming from 3GPP, include multiple cell layers, but only by using mathematical formulas that yield to a regular network topology [3GP10]. Furthermore, the path loss predictions used come from simplified propagation models and not from sophisticated (path loss) prediction tools, such as ray-tracing or ray-launching [Sar+03]. To visualise the difference between the two approaches, Figure 2.1a gives an example for a classical 3GPP ("wrap-around") scenario. Clear cell borders are visible as well as the regular network topology with a predefined inter-site distance. On the other hand, Figure 2.1b shows a realistically planned LTE network (operating at 1800 MHz). Compared to the 3GPP scenario, the topology is inhomogeneous, and the prediction tool used (3D ray-tracing) leads to scattered and indistinct cell borders. The authors of [Ros+12] also compared major differences between the two approaches. Larger parts of these *realistic* scenarios were developed and used in the PhD thesis of Thomas Jansen [Jan16] and the work of Dennis M. Rose. Moreover, the scientific community picked up and also further expanded the outcome. For example, the European Union funded Seventh Framework Programme (FP7) project on Self-Optimisation and self-ConfiguRATion in wirelEss networkS (SOCRATES) (partially) and also the FP7 project on SElf-MAnagement FOr Unified Heterogeneous Radio Access Networks (SEMAFOUR) extensively relied on realistic scenarios for their simulation work. For the remainder, this thesis only considers such realistic network scenarios since an additional consideration and comparison with (unrealistic) hexagonal systems would go way beyond the scope of the following discussions.



(a) Based on 3GPP [3GP10] (b) Realistically planned

Figure 2.1: Two different network topologies and the respective best server areas

Typically, to simulate mobile networks, two techniques (or "views") can be applied. One of the two techniques is the so-called *macroscopic* view, which looks at larger time spans of days, weeks or even months (see subsection 2.1.1). Here the focus lies on the evolution of the network regarding data traffic demands and global path loss and interference statistics. Another method with a much finer temporal granularity, where more details can be simulated and observed, is the so-called *microscopic* view. Due to the high computational complexity, typical simulation times cover minutes or hours (see subsection 2.1.2). With this simulation approach, short-term varieties concerning signal strength conditions or cell load profiles can be simulated. However, both (simulation) views have their advantages and disadvantages as the following subsections will show.

(a) 9 am **(b)** 9 pm

Figure 2.2: Two traffic intensity maps at different times of day based on [RBK14]

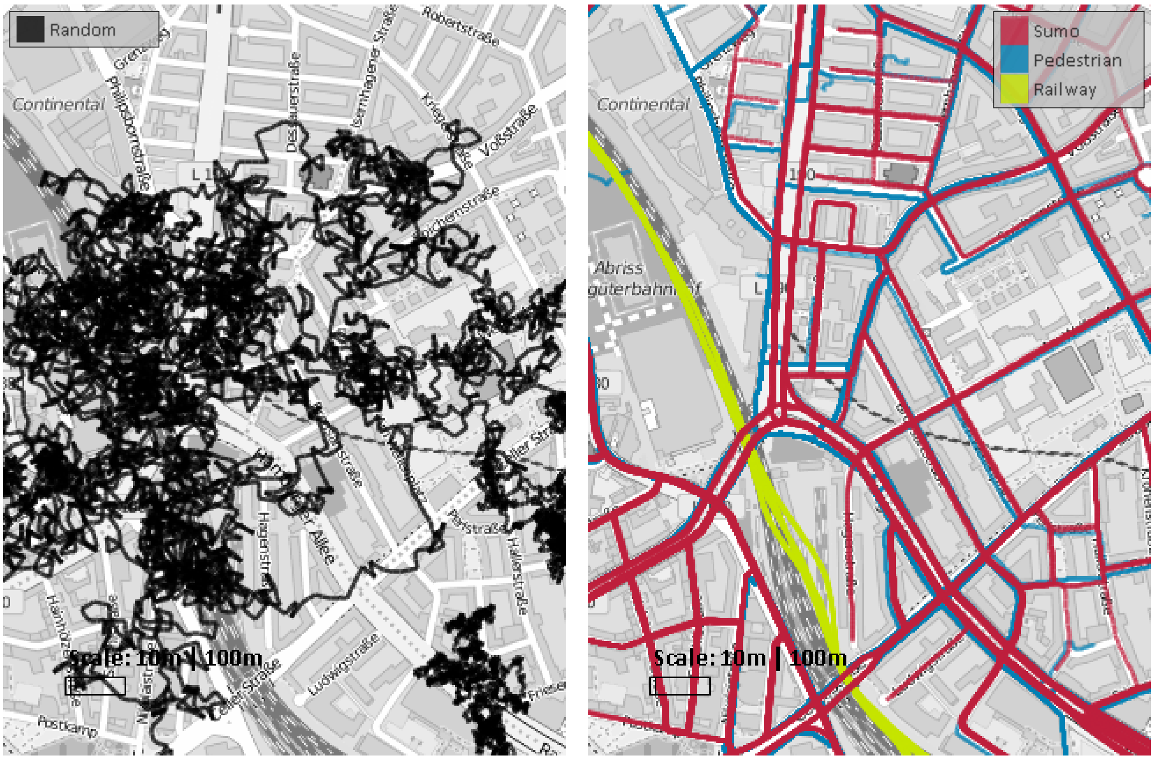
2.1.1 Macroscopic View

Figure 2.2 presents two different data traffic intensity maps. Such maps indicate how much data gets requested for a given period (usually 30 minutes or one hour) per pixel of the map (usually 1 pixel complies with an area of $10\,\mathrm{m} \times 10\,\mathrm{m}$). As it is clearly visible in Figure 2.2a and Figure 2.2b, the traffic intensity varies in time and space. Hence, there is a higher traffic demand in the city centre during morning hours, compared to evening hours when the traffic demand is more concentrated in the rural and living areas of the city. This clearly implies some level of mobility in the mobile network. Traffic intensity maps are well suited to run long-term evaluations regarding network performance or traffic evolutions since such maps usually change with the temporal resolution of 30 to 60 minutes. The authors of [RBK14] have proposed a method how to generate these maps from real KPI measurements. Evaluation examples using macroscopic simulations can be found in [Hof+15], [Tri+15] and in a student thesis[1]. The major disadvantage, which is also the reason why this thesis does not consider such network simulations, is that it is almost impossible to derive individual user events (such as Handover (HO), Ping-Pong Handover (PP), Handover Failure (HOF) and Radio-Link-Failure (RLF) counters) due to the lack of actual moving subscribers in the system. To produce such events respective user mobility models and an implemented HO algorithm that handles the connections from all users to the cells are required.

2.1.2 Microscopic View

To overcome the disadvantages of the *macroscopic* view (i.e. missing user events), the *microscopic* view focuses on individual movements and user behaviours in the mobile radio network. This view can be achieved by generating and simulating respective user trajectories that follow predefined paths. In combination with an implemented HO algorithm [3GP13], such movements eventually lead to HO, PP, HOF and RLF events. Now, how such movements are generated and look like depend on the level of complexity one can put into the mobility modelling. For that, two examples of user movements are given in Figure 2.3. On the left side, a fairly *unrealistic* behaviour is shown (black lines). These "random walk" mobilities are also often used and easy to generate. After uniformly "dropping" users over the entire simulation area, the direction and distance are chosen randomly in every step of the simulation, leading to this erratic behaviour. The user movements on the right feature different *realistic* mobility models, such as vehicles travelling on roads (red lines), pedestrians walking on pavements (blue lines) and trains entering and leaving the central station (green lines). For this thesis, several realistic mobility models are introduced, explained and evaluated in detail in chapter 3 regarding different Handover Performance Indicator (HPI) metrics, such as the Handover Success Ratio (HOSR). The users themselves generate the respective data traffic in the mobile network. The exact time, duration and required data rate are defined by using a so-called traffic call model. A call model can be very simple, ranging from producing a Constant Bit Rate (CBR) data traffic or a rather complex one with different settings for particular service types, durations of usage and inter-arrival times between the termination and the beginning of a new session. The herein applied advanced data traffic model with the different service types will be further explained in chapter 4.

[1] S. R. Ferran, "Implementation and Evaluation of a Self-Organizing-Network-Algorithm", Masterarbeit, Technische Universität Braunschweig, Institut für Nachrichtentechnik, Dipl. 14/006, 2014



(a) Random walk mobility model **(b)** Realistic mobility mix

Figure 2.3: Two different mobility mixes in the simulation scenario

2.1.3 Network Topology

This thesis focuses on altering the performance of a multi-layer and multi-RAT system to account for the ever increasing complexity of modern radio networks. Therefore two radio access technologies and two layers are considered, respectively.

2.1.3.1 Radio Access Technologies

The RATs that are used here are LTE and WLAN[2]. These two technologies can provide good spectral efficiencies and thus high cell throughputs (cf. section 2.3), which is crucial to cope with the data traffic demands of the users in a mobile radio network. Other technologies could have been used as well, e.g. GSM or UMTS, but are neglected to reduce the already high complexity of the large-scale network scenarios employed. Furthermore, only the *downlink* is considered and investigated in this thesis, because the SON functions used only change (radio) parameters of the base stations. The User Equipment (UE) configurations will remain the same. Also, the main data traffic requirements originate in the downlink, so from the base stations to the UEs.

[2]Please note that in the following only the synonym WiFi is used instead of WLAN. Meant, however, is still always the standardised version coming from the IEEE.

Theoretically it is possible to simulate the uplink parameters as well. However, this would drastically increase the simulation durations and no further benefit regarding the expected results can be foreseen. In the following, a short overview and introduction of the two RATs are given.

LTE: With Release 8 of the 3GPP specifications [3GP09] general design flaws of UMTS ought to be addressed. For example, the spreading of the signal over the entire (and fixed) carrier bandwidth of 5 MHz in UMTS that leads to adverse effects due to multipath fading. In principle, the LTE network architecture is quite similar to legacy technologies such as GSM or UMTS. However, LTE solely relies on an all Internet Protocol (IP)-based core network with clear structural solutions. An overview of the components of the Evolved Packet System (EPS), containing the air interface Evolved UMTS Terrestrial Radio Access Network (EUTRAN) and the Evolved Packet Core (EPC), is shown in Figure 2.4.

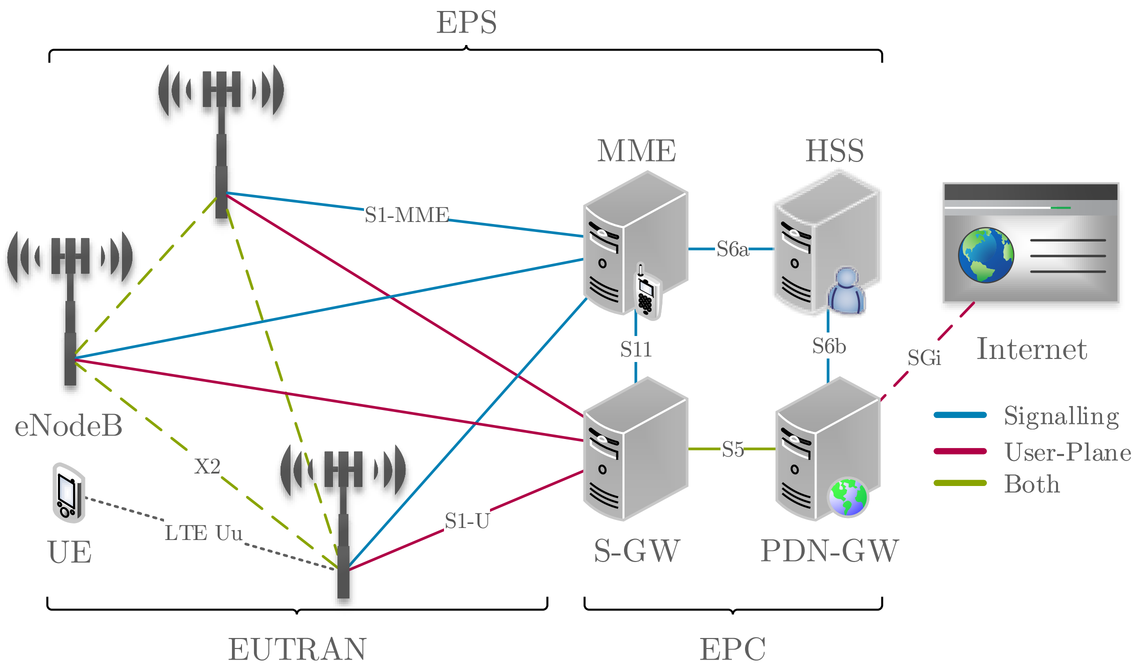


Figure 2.4: Architecture overview of LTE [Sau11, p. 208]

The core network, i.e. the EPC, includes four elements:

- **S-GW:** The Serving Gateway (S-GW) is connected to a dedicated part of the EUTRAN and handles the IP routing.
- **PDN-GW:** The Public Data Network Gateway (PDN-GW) is connected via the “S5” interface to the S-GW and provides a connection to the data network (i.e. Internet).

- **MME:** The Mobility Management Entity (MME) is, like the S-GW, also connected to the EUTRAN and handles the administration, localisation and roaming of the UEs in the network.
- **HSS:** The Home Subscriber Server (HSS) is a database that contains information about, e.g., specific subscriptions of each user/subscriber in the network.

The EUTRAN contains the air interface which connects the UEs with the evolved Node Bs (eNBs), i.e. the base stations, and makes use of Orthogonal Frequency Division Multiplexing (OFDM) with different types of Modulation and Coding Schemes (MCSs) to transmit the data. The schemes, as well as the bandwidth used, can be dynamically adapted based on the signal strength and interference conditions of the users [Sau11, pp. 205]. In addition, the eNBs are connected over the “X2” interface to exchange, e.g., load information [3GP16]. For further reading, [Jan16, pp. 7] explains the LTE air interface and the physical layer in great detail.

WiFi: WiFi has been standardised by the IEEE in the 802.11 specifications. With WiFi, the *wired* Local Area Network (LAN) system (IEEE 802.3 standards) has been adapted to fit the needs of a more and more mobile connected world. Two primary classifications of the elements used in a WiFi network can be made:

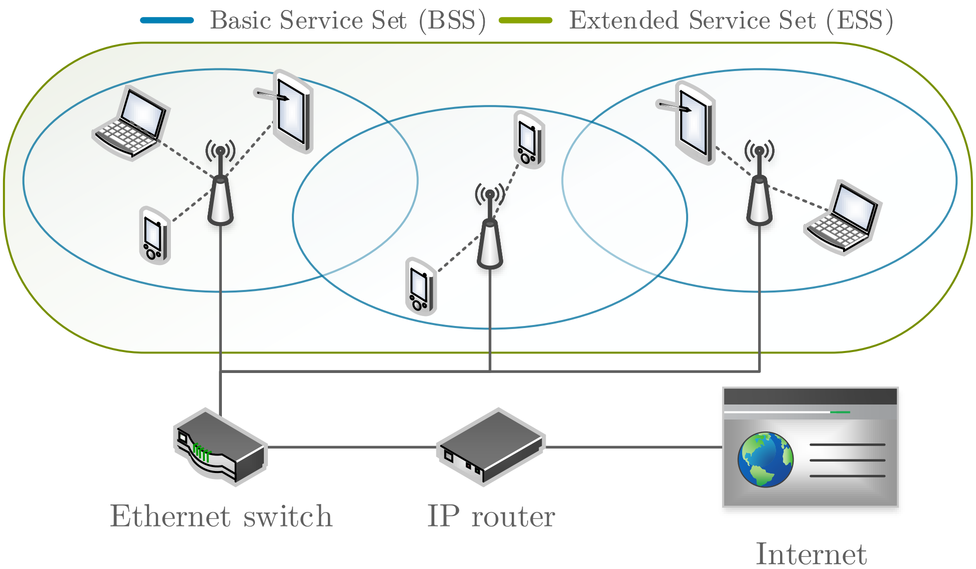


Figure 2.5: Architecture overview of WiFi [Sau11, p. 325]

- **BSS:** An (infrastructure) Basic Service Set (BSS) combines the basic components of an 802.11 WiFi, that is, an Access Point (AP) and all devices in the reception area of the AP. The AP provides the gateway to the Internet via an IP router.

Compared to an independent BSS (also know as *Ad-Hoc* mode), the devices do not communicate directly with each other, but via the AP only. This also means that all data have to be transmitted twice – from the device to the AP and from the AP to the device. However, an infrastructure mode can extend the coverage of WiFi by allowing more devices to communicate which each other.

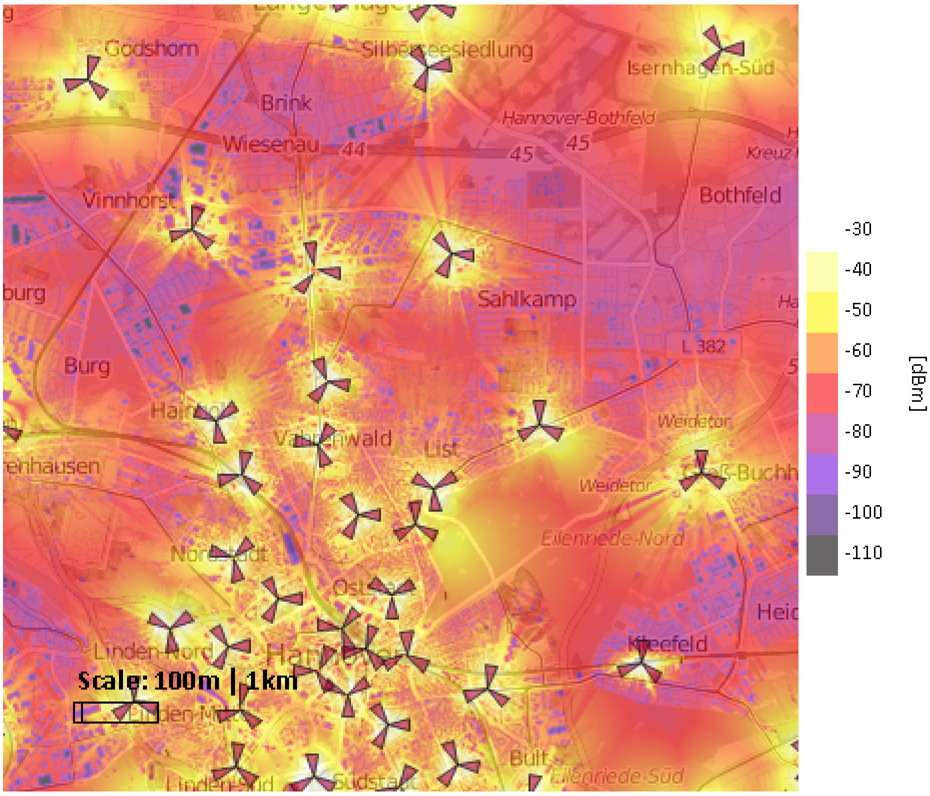
- **ESS:** Multiple BSS, connected over an Ethernet connection, compose an Extended Service Set (ESS). With that, the disadvantage of a limited reception of a single BSS is resolvable by building a distributed system of APs that provide sufficient coverage. ESSs can often be found in major public areas such as shopping malls or airports.

Several BSSs that build an ESS are also illustrated in Figure 2.5 [Sau11, pp. 321]. Furthermore, [Nuc15, pp. 13] provides a detailed description of the physical layer of IEEE WiFi systems. This concludes the overview of the two RATs that are used in this thesis. The two cell layers will follow now.

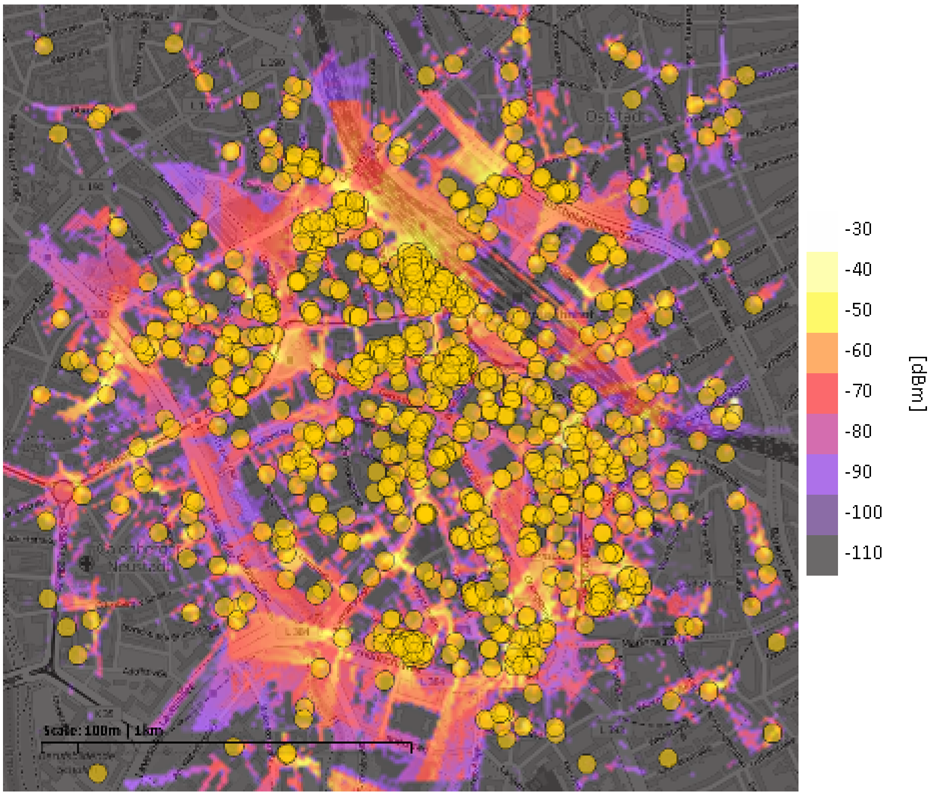
2.1.3.2 Cell Layers

One strategy to provide additional capacity is to increase the cell density. This increment is achievable by decreasing the inter-site distances, e.g., bringing the cells closer together. Another possibility is to add cell layers which usually operate at different frequencies. Here, two cell layers are considered: An LTE macro layer, operating at 1800 MHz, and a WiFi small cell layer at 2400 MHz.

Macro Cells: A macro cell layer usually covers larger parts of the network to provide sufficient coverage. An example showing sites of this kind of cell layer is given in Figure 2.6a. Furthermore, the received signal strengths are shown as a coverage map in the background. Two observations can be made. Firstly, in the city centre, the site density is much higher compared to the areas which mostly cover rural parts. This greater density is mainly due to the higher data traffic demands in (deep) urban areas (compare also the intensity maps from Figure 2.2). Secondly, the signal strengths provide good coverage in almost the entire area, because the transmit power is set at 46 dBm. This indicates fewer coverage holes and, hence, a potentially good Quality of Service (QoS). However, one cell covering a large area means that also a lot of users can connect to that cell. This might lead to a situation where the connected users compete against other users to get a fraction of the available resources, resulting in low data rates per user and a bad Quality of Experience (QoE). Please note that the scenarios used will be explained in much more detail in chapter 4.



(a) Macro layer (here: LTE cells)



(b) Small cells (here: WiFi APs)

Figure 2.6: Received signal strengths for different cell layers

Small Cells: The planning and prediction of a small cell layer in the scenario used were realised in a master thesis[3] that included over 1000 small cells in the inner-city of Hanover, Germany. Figure 2.6b shows the resulting site locations and coverage prediction for this layer. Note that every cell is considered here as *small* that operates with a transmit power of 23 dBm or less. Besides the obviously higher amount of cells compared to the macro cell layer, the small cell layer can barely provide coverage outside the immediate vicinity of the cell location. These radical signal strength variations also lead to increased probabilities of HOF events which translate into a rather bad QoS. However, if a user connects to a small cell, the resources of that cell can be mostly allocated to that user. This way, high data rates and low latencies, i.e. a good QoE, can be assured. Eventually, this layer also includes several WiFi ESSs, located in shopping malls and the train station.

2.1.4 SiMoNe – Simulator for Mobile Networks

All simulations that are carried out for this thesis are conducted by using the system-level simulation tool called Simulator for Mobile Networks (SiMoNe). SiMoNe has been developed by the department for Mobile Radio System at the Institute for Communication Technologies of the Technische Universität Braunschweig, where Dennis M. Rose designed major parts of it [Ros+15]. With SiMoNe it is possible to simulate and visualise various aspects of a modern mobile radio network with a diverse degree of complexity. Ranging from small-scale scenarios focusing on specific scientific problems, going up to large-scale systems with multiple RATs and cell layers. All relevant data (i.e. geographical information, path loss predictions, etc.) is stored in a Structured Query Language (SQL) database, providing an efficient interface towards SiMoNe. As illustrated in Figure 2.7, a high-performance visualisation can also be attached to demonstrate, e.g., user mobility, path loss prediction maps or SON function activities (cf. [RHK16]).

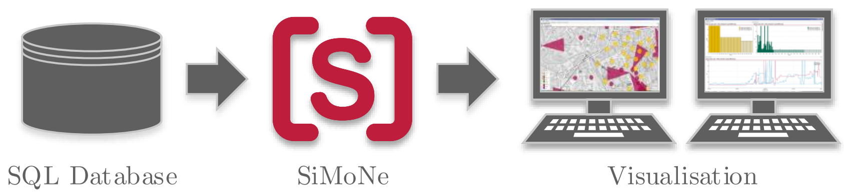


Figure 2.7: Simulator for Mobile Networks (SiMoNe)

[3] B. Heckmanns, "Planung und Simulation von LTE-Femto-Zellnetz im Hannover-Szenario", Masterarbeit, Technische Universität Braunschweig, Institut für Nachrichtentechnik, Dipl. 15/009, 2015

A simulation concept was introduced in SiMoNe allowing a flexible adjustment of mobile radio network aspects that are needed to be simulated to ensure the handling of this huge degree of (varying) complexity. This so-called “block concept” is shown in Figure 2.8. A “block” usually consists of *inputs*, a *functional logic* inside the block and *state* information. The inputs provide necessary initial values so that the logic of the block can transform these values. The outcome is then stored as state information that can be used as initial values for the ensuing blocks (dashed block on the right). For instance, if the Signal-to-Interference plus Noise Ratio (SINR) of the user (which will be a new state information) needs to be calculated (which is the logic of the block), the signal strengths have to be available (input values). One other simple example to illustrate all components of the block concept is a “signal strength block”. The new *state* information of the block is the path loss prediction for a scenario at a given moment in (simulation) time. The *inputs* needed are a “SQL-connection” to gather the available predictions, a “(time) controller” to receive the current (simulation) time and a “scenario” block to know the boundaries of the area. Finally, the *functional logic* takes over the user positions, path loss predictions at a given point in time and updates the corresponding signal strength values.

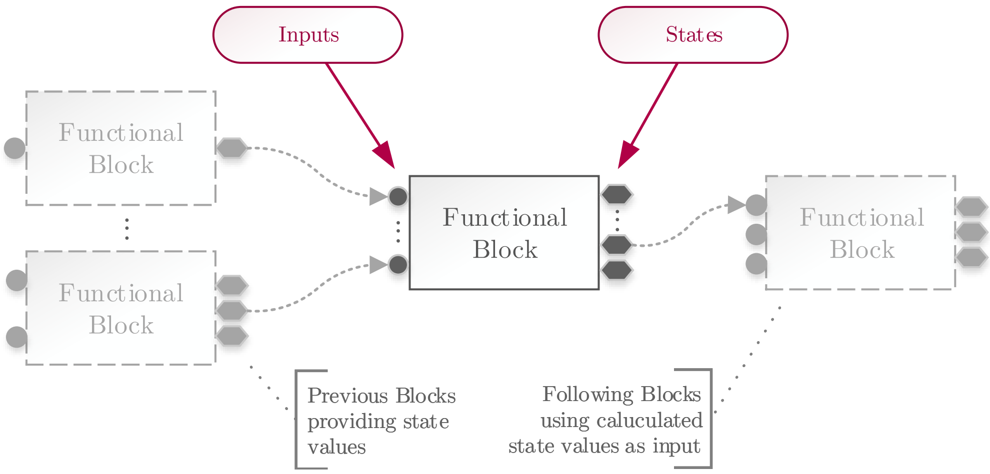


Figure 2.8: A functional block in SiMoNe with inputs and states

Now, all necessary *blocks* for a given simulation need to be connected and ordered in a logical way. As shown in Figure 2.9, this can be done in SiMoNe by defining a so-called *flow* of blocks. A block *caller* (filled grey block) sequentially executes each block in the pre-defined order, that is, from top to bottom. All basic functionalities, i.e. scenario data, signal strength or HO procedure, are shown in grey. The SINR calculation (blue blocks) is done in an iterative way (for further explanations see section 2.3 and [Jan16, p. 59]), thus a second *caller* block (“SINR Caller”) is needed. Marked in red are additional blocks that were developed and added for this thesis. Such blocks can also change the state information values of previous blocks. For example, a SON function adjusts a cell parameter. For that, the corresponding state values (e.g. cell power or antenna tilt) need to be re-configured in the "Scenario Data" block. In the end, the desired states of different blocks can be stored in a logger allowing additional evaluations later on, for instance in MATLAB [MAT17] or Python [Pyt17].

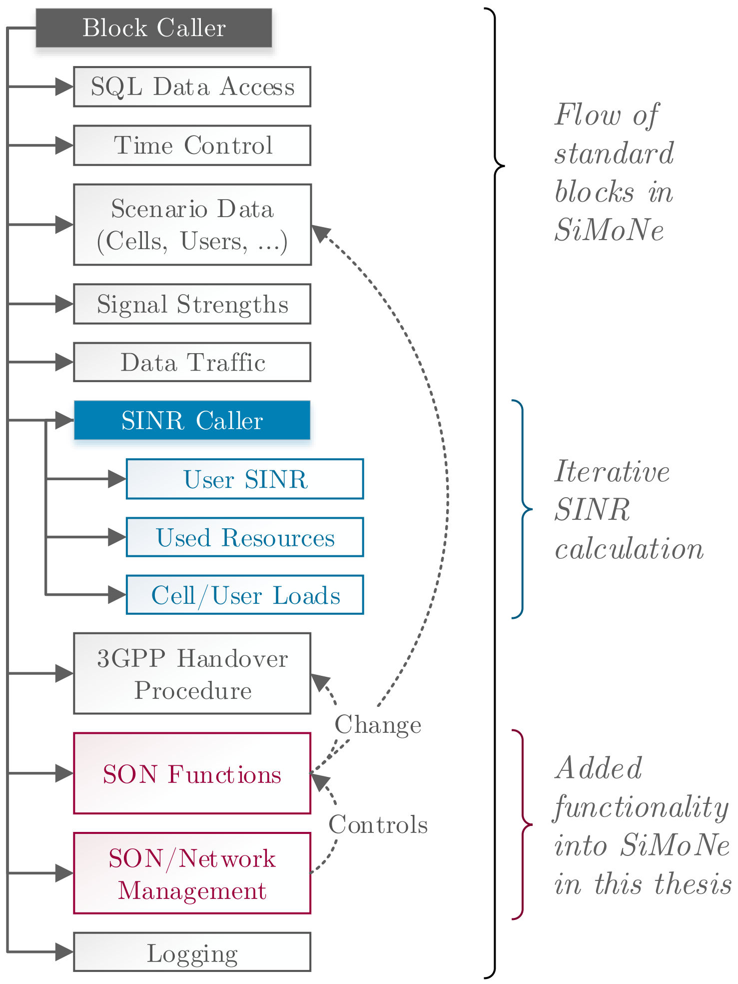


Figure 2.9: Simplified example of connections of blocks to simulate SON function and network management functionality using SiMoNe

2.2 Self-Organising Network Functions

This section explains the three Self-Organising Network (SON) functions that are examined in detail in chapter 5 and that are used to alter a mobile network so that the performance is in line with pre-defined operator goals (cf. chapter 6). The three functions are: LTE Load Balancing (LB), LTE Robustness Optimisation (RO) and LTE/WiFi Traffic Steering (TS). The first two functions tackle mobility aspects in the network by changing HO parameters. The latter function makes use of the two RATs and the cell layers (see subsection 2.1.3) and steers the traffic among the two technologies. Before the individual SON functions are explained in detail, a short overview of SON in general is given.

Since the first definition of use cases for SONs by the Next Generation Mobile Networks (NGMN) Alliance, a coalition of major operators and vendors from all over the world, many kinds of research have been done to solve problems in the network automatically and assist the MNO in reducing time-consuming (manual) work. Several requirements and application areas have been defined in [NGM07b] and [NGM07a]. These SON use cases can roughly be grouped into three categories, namely: self-configuration, self-optimisation and self-healing. All three topics have been addressed by the EU funded FP7 project SOCRATES [Kür+10], where the Institute for Communications Technology from the Technische Universität Braunschweig was involved in designing scenarios and developing first SON functions. The project had a runtime of three years and started in 2008. Eventually, the mobile networks became more and more evolved by introducing new RATs, and more cell layers. The follow-up EU FP7 project SEMAFOUR [Hah+15b] developed and designed SON functions that optimised the network with respect to the increased complexity. Also, (self-organising) network management functionality has been identified as a research topic to give MNOs the possibility to define KPI objectives and coordinate the SON functions in an efficient manner. The project also had a runtime of three years and started in 2012. But not only MNOs, vendors (including NGMN), and the academic community saw SON as a crucial step to make the networks more efficient and resilient towards changes (e.g. increasing mobile data demands, varying mobility behaviour, etc.). 3GPP picked up and continued the work in 2008 [3GP11], [3GP13]. For more general information on the topic of SONs, the reader is also referred to [HSS12] and [RH12].

As mentioned, this thesis focuses on self-*optimisation*. Figure 2.10 illustrates this general concept. At first, (KPI) measurements are taken. After that, the SON algorithm processes the measurements and decides on (radio) parameter changes. Such adjustments are then enforced in the network, and the (self-optimisation) cycle starts all over again. Note that the SON function in Figure 2.10 features gears on top that shall symbolise the ability to change the underlying algorithm of the SON function. Changing, e.g. the step size, threshold or KPI ranges, modifies the behaviour of the algorithm as well. This behavioural change of the SON functions is most likely reflected

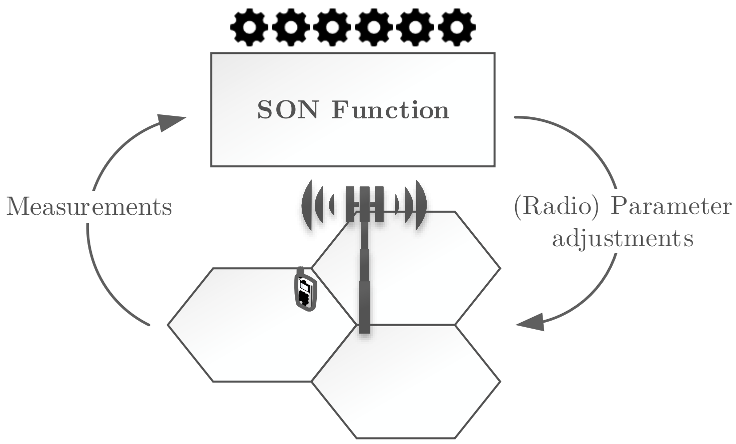


Figure 2.10: Basic SON functionality

in the network KPIs so that the system is steerable towards the desired performance. The so-called SON Function Configuration Parameters (SCPs) and the corresponding SON Function Configuration Values (SCVs) are explained for each SON function in the following subsections.

2.2.1 LTE Load Balancing

The objective of LB is to distribute the cell load in the system equally. By that, the function is supposed to provide a better QoE for the subscribers in the mobile network. The LB algorithm is triggered if the load of a Source evolved Node B (SeNB) is above a predefined threshold value (cf. the parameter "maximum load" in Table 2.1). After passing the load threshold, the SON function tries to lower the (SeNB) load until a certain load value ("SeNB load") is reached and the SON activity stops. The algorithm reduces the load by adjusting the Cell Individual Offset (CIO) between the SeNB and a potential Target evolved Node B (TeNB) to shift and keep users from highly loaded cells to less loaded neighbouring cells. Figure 2.11 illustrates the concept. CIO values change the *virtual* cell borders, which will be considered in the HO procedure. The actual CIO value is reached with a certain step size ("CIO step size"). The only constraints for the LB function are that the load at the TeNB stays below a certain value ("TeNB load") and the CIO is below a maximum value ("CIO maximum"). Load values between cells can be exchanged in LTE with the "X2" interface [3GP16]. The Period of SON execution (PSON) is fixed and set at one second.

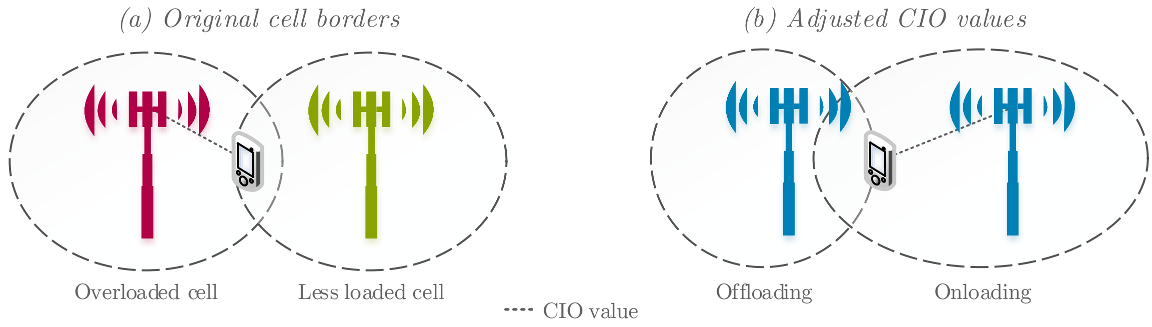


Figure 2.11: Principle of the LTE LB SON function

The SCPs used are again described in Table 2.1 and all LB SCV combinations are listed in Table A.1 in the appendix. For more information on the LB function used the reader is referred to [Lob+10].

Table 2.1: LTE LB SCPs

Parameter	Unit	Description
Maximum load	[%]	Threshold after LB function is triggered
SeNB load	[%]	Maximum (desired) load value at the SeNB
TeNB load	[%]	Maximum load at the TeNB
CIO maximum	[dB]	Maximum allowed CIO value
CIO step size	[dB]	Step size to reach the CIO value

2.2.2 LTE Robustness Optimisation

RO aims at improving the Handover Performance (HP) by optimising the HO decision point with Hysteresis (HYS) and Time-To-Trigger (TTT) value pair adjustments (see also Figure 2.12). This optimisation goal is to provide a better QoS for the subscribers in the network due to less HOF or RLF events. This HO improvement is done by collecting HO statistics over time. Based on the previous HP, the RO function then changes the parameters accordingly. In this thesis, a RO function according to [Jan+10], [Jan+11] and [Bal+11] is used. This implementation allows for two methods in order to change network parameters (cf. the parameter "evaluation method" in Table 2.2). One method is called "window". Here the function monitors the HO statistics for a given period ("evaluation window"). After this duration, the function enforces parameter changes. The other method is called "event". Again, the algorithm collects HO statistics and if a certain amount of events is reached ("number of HO events"), the parameter changes are enforced.

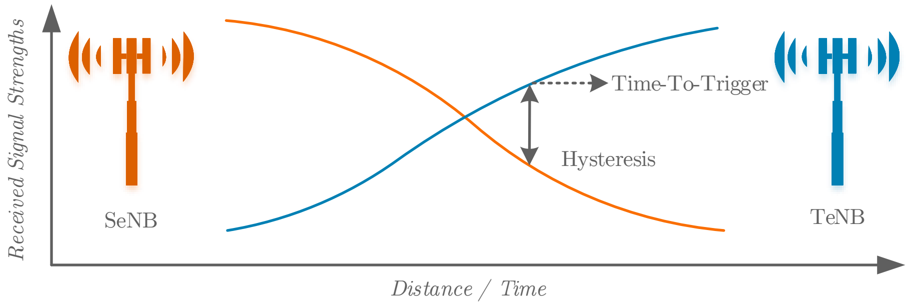


Figure 2.12: Principle of the LTE RO SON function

All potential RO SCV combinations are listed in Table 2.2. The RO SCPs are described in Table A.2. Moreover, a thorough analysis of handover improvements in hexagonal and realistic scenarios can be found in [Jan16, pp. 143].

Table 2.2: LTE RO SCPs

Parameter	Unit	Description
Evaluation method	N/A	RO function is either "window"- or "event"-based
Evaluation window	[sec]	Period of time until the RO function is triggered
Number of HO events	[#]	Number of HO events until the RO function is triggered

2.2.3 LTE/WiFi Traffic Steering

TS tries to control the mobile data traffic between different RATs. One possibility is to steer the data traffic between LTE and WiFi, as it was investigated in the SEMAFOUR project with the TS use case [Kov+14], [Wan+14] and [Wil+16]. Decisions on whether a user should connect to either LTE or WiFi can be made based on the (average) cell loads. If the load is high in LTE (above "load threshold high"), the subscribers are steered to WiFi. If, on the other hand, the WiFi network is highly loaded, the algorithm steers the subscribers to the LTE cells. The steering itself is achieved by changing the WiFi Received Signal Strength (RSS) selection threshold, which determines when a user connects to WiFi. Similar to the LB function, a step size ("RSS threshold step size") is used to determine the best RSS values. If the RSS is low, e.g. -90 dBm, a HO command to WiFi becomes more likely. If the value is high, e.g. -30 dBm, the (virtual) cell size of the WiFi AP is reduced and a HO command becomes unlikely. Figure 2.13 also shows the procedure. The TS decisions are executed after a certain period (PSON).

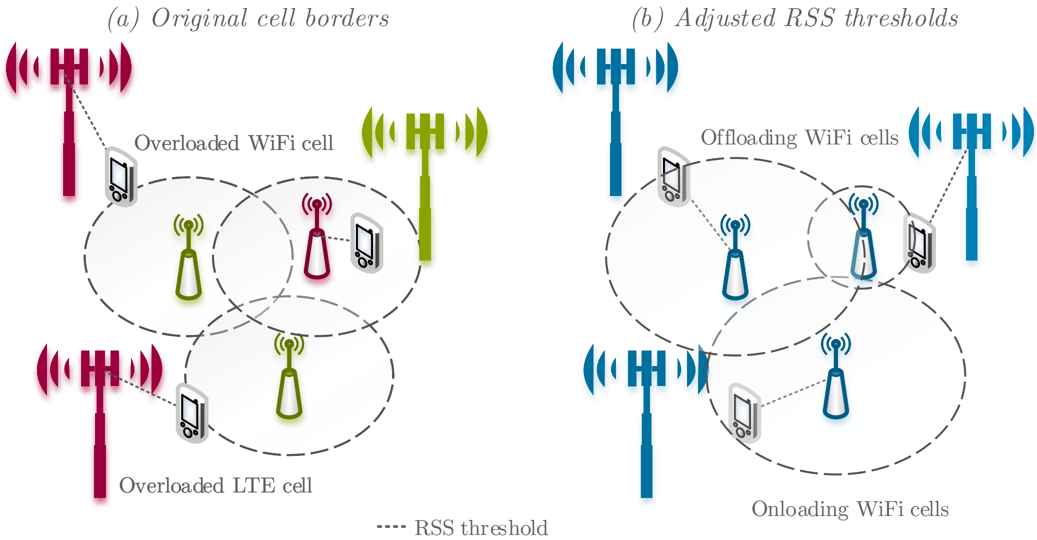


Figure 2.13: Principle of the LTE/WiFi TS SON function

Table 2.3 lists the TS SCPs used. All possible SCV combinations are listed in the appendix in Table A.3. For more information on TS the reader is also referred to [Hah+15b, pp. 40].

Table 2.3: LTE/WiFi TS SCPs

Parameter	Unit	Description
PSON	[sec]	Period of TS execution
RSS threshold step size	[dB]	Step size to adjust the RSS threshold
Load threshold low	[%]	Load value to consider cell as less loaded
Load threshold high	[%]	Load value to consider cell as highly loaded

2.3 Key Performance Indicators

For the course of this thesis, four Key Performance Indicators (KPIs) are used in order to evaluate the performance of the mobile networks. These KPIs are: the *cell load*, *cell throughput*, *fraction of unsatisfied users* and the *handover success ratio*. All four KPIs are defined and explained in detail in the following subsections.

2.3.1 Cell Load

The term “load” can be interpreted as a fraction of the *required* resources divided by the total number of *available* resources. Now, to determine an achievable throughput value per Physical Resource Block (PRB) (R_u), a mapping function ($R(\cdot)$) between the user SINR ($SINR_u$) and the spectral efficiency is needed. Equation 2.1 is expressing this relationship:

$$R_u = R(SINR_u) \tag{2.1}$$

Two exemplary curves for such mappings are given in Figure 2.14. Additionally, it shows the Shannon limit as a dashed black line [Sha48]. One can see that the spectral efficiency for LTE (shown in red) is quite close to that formulated limit. WiFi[4], on the other hand (shown in blue), is farther away from that limit. The LTE mapping used is taken from [BK14]. The WiFi mapping is an outcome of a master thesis[5]. A particular weighing factor has been introduced for WiFi to account for the random back-off times due to the collision avoidance in Carrier Sense Multiple Access (CSMA) systems. The factor is set at 0.68 which is in line with results coming from [Gar+13]. Also, note that the minimum SINR value is -6.5 dB for LTE [3GP15] and 0 dB for WiFi. This value expresses a threshold below which no communication between cell/AP and UE is possible. For completeness, the actual step functions coming from the different MCSs are plotted as red [3GP17a, p. 173 (Table 7.2.3-1)] and blue [Nag17] light dashed lines.

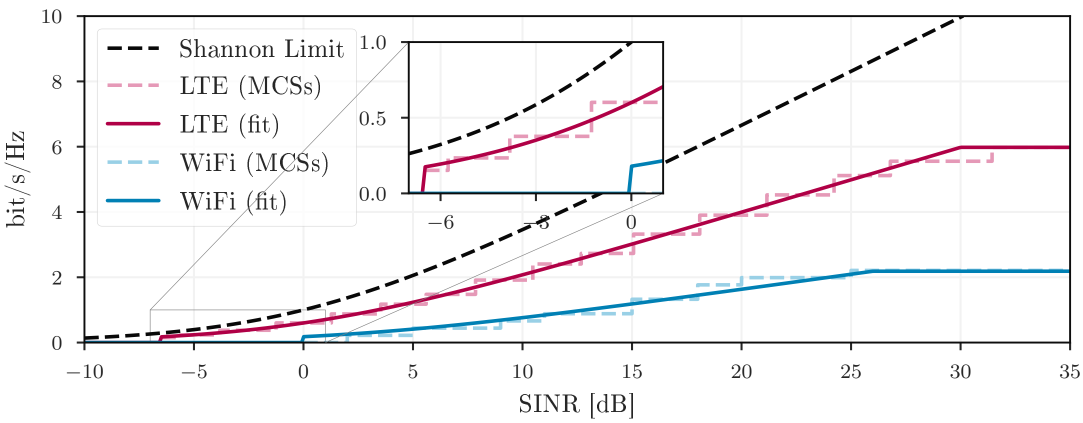


Figure 2.14: Spectral efficiency for the two technologies

[4]Based on the IEEE 802.11n standard in the following

[5]P. Becker, “Implementierung und Evaluierung eines SON Algorithmus für LTE/WiFi Traffic-Steering”, Masterarbeit, Technische Universität Braunschweig, Institut für Nachrichtentechnik, Dipl. 16/006, 2016

The theoretically achievable (user) throughput can be given by multiplying the (approximated) spectral efficiency of Figure 2.14 with the bandwidth used of the cell/AP, which Figure 2.15 depicts [BK14]. In the following, LTE cells are assumed to be operating with a bandwidth of 10 MHz and WiFi cells with 20 MHz which both fully contribute to the interfering power. These different bandwidths also bring the two throughput curves much closer together, compared to the spectral efficiency shown in Figure 2.14.

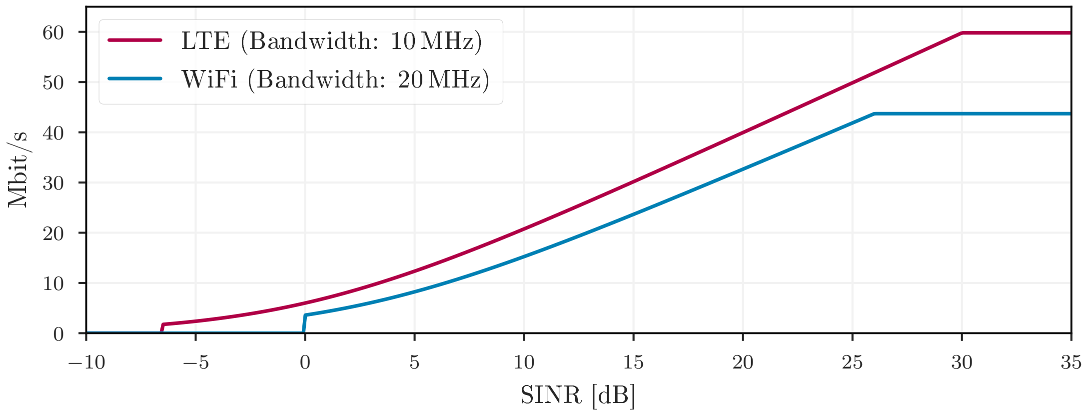


Figure 2.15: Maximum achievable throughput for the two technologies

Now, with a given *requested* user data rate (D_u), a user SINR ($SINR_u$) and the throughput mapping (R_u) from Equation 2.1, the amount of *required* resources ($\hat{N}_u$) can be expressed in the following way:

$$\hat{N}_u = \frac{D_u}{R(SINR_u)} = \frac{D_u}{R_u} \tag{2.2}$$

Finally, the (downlink) cell load (ρ_c) is the total amount of required user resources (i.e. the sum over $\hat{N}_u$ of all users connected to that cell in Hz), divided by the number of available cell resources (N_{total}, i.e. the bandwidth of the cell also in Hz):

$$\rho_c = min\left(1, \frac{\sum_{u|X(u)=c} \hat{N}_u}{N_{total}}\right), \tag{2.3}$$

where $X(u)$ is the so-called connection function, which determines whether a user is connected to a particular cell or not. Note that the cell load cannot exceed 1 (i.e. 100 %). If the sum of all required resources ($\hat{N}_u$) would cause the load to exceed 1, the requested user data rates (D_u) are scaled down accordingly to get the achieved data rates ($\hat{D}_u$). Now, the cell load (ρ_c) relies on the user SINRs ($SINR_u$). As Equation 2.4 shows, the SINR calculation also depends on the cell load (multiplication with the interference term in the denominator). Here, S denotes for the receiving signal, N for the noise term and I for the power of the respective interferer [Jan16, pp. 56].

$$SINR_u = \frac{S_{X(u)}}{N + \sum_{c \neq X(u)} \rho_c \cdot I_c} \tag{2.4}$$

This cell load dependency (see ρ_c in the denominator of Equation 2.4) leads to an equation system that is solvable by using an iteration procedure (see also blue blocks of Figure 2.9). The result is that in each simulation step the cell load values are calculated based on the given user SINR. This calculation is repeated until the cell load values do not change significantly any more after each iteration step (usually a threshold of 1 % is assumed) or a maximum number of iterations is reached (often set at a value of 10 to 25).

2.3.2 Cell Throughput

After the cell load calculation is done, the *cell* Throughput (TP) (τ_c) can be derived by accumulating the achieved *user* TPs ($\hat{D}_u$) from all connected users, see Equation 2.5:

$$\tau_c = \sum_{u|X(u)} \hat{D}_u \tag{2.5}$$

The (maximum) cell TP is a valuable KPI for the MNO because it gives a direct and definite indication of the performance of the network. For that, an MNO is keen to keep the cell TP (and, thus, also the user TP) values as high as possible to, e.g., advertise the system performance capabilities towards (potentially new) costumers.

2.3.3 Unsatisfied Users

Besides the throughput and the load of a cell, which are valuable indicators regarding network utilisation, the user satisfaction gives a direct indicator about the QoE of the system. Usually, an MNO is eager to improve this quality indicator because a satisfied customer is likely to extend existing contracts and, thus, create more revenue. A KPI definition from [VDL09] is used to measure user dissatisfaction, which of course should be as low as possible. For that, the *virtual* cell load $\hat{\rho}_c$ is considered (cf. Equation 2.6). The only difference compared to the cell load is the fact that here the values can exceed 1 (i.e. 100 %). This new formulation gives a direct indication of how "overloaded" a cell is. For example, if $\hat{\rho}$ equals 1.5, the cell would need half of the available resources in addition to serve – and thus satisfy – all users in that cell.

$$\hat{\rho}_c = \frac{\sum_{u|X(u)} \hat{N}_u}{N_{total}} \tag{2.6}$$

Finally, the fraction of Unsatisfied Users (UUs) (υ_c) is calculated based on Equation 2.7. If $\hat{\rho}_c$ is less or equals 1, no user in that cell is unsatisfied. If the value equals for example 3, two-thirds of the connected users would be dissatisfied.

$$\upsilon_c = max\left(0, 1 - \frac{1}{\hat{\rho}_c}\right) \tag{2.7}$$

To conclude, the cell load does not indicate to what extent values might exceed 100 %. As soon as a cell is in overload, the user becomes unsatisfied. The degree of *dissatisfaction* can be measured with Equation 2.7. In a real system such information might be acquired by looking at the scheduling decisions in the eNBs and comparing them with the requested data rates of the users.

2.3.4 Handover Success Ratio

The HO behaviour in a mobile network is another leading performance indicator for an MNO. It largely determines the QoS level in the system. In the worst case, if every HO event leads into a Handover Failure (HOF), the reputation of the service provider decreases drastically. On the other hand, signalling traffic, which is caused by each HO event, can significantly strain the network performance if the system executes HO commands too often or if the HO was even unnecessary in the first place. Hence, the MNO wants the best compromise between offered QoS and increased data traffic due to signalling. The number of HO events ($N_{ho-events}$) are needed to measure the performance. $N_{ho-events}$ are the sum of Ping-Pong Handover (PP) (N_{PP}), non-PP (N_{non-PP}), HOF (N_{HOF}) and Radio-Link-Failure (RLF) events (N_{RLF}):

$$N_{ho-events} = N_{PP} + N_{non-PP} + N_{HOF} + N_{RLF} \tag{2.8}$$

Additionally, the total number of successful (cf. Equation 2.9) and unsuccessful HO (cf. Equation 2.10) events are needed. The first one is the sum of PP and non-PP events. The latter is the sum of HOF and RLF events.

$$N_{ho-succ} = N_{PP} + N_{non-PP} \tag{2.9}$$

$$N_{ho-fail} = N_{HOF} + N_{RLF} \tag{2.10}$$

With the given number of successful HOs, it is possible to calculate a Handover Performance Indicator (HPI) that accounts for the ratio of successfully executed HO commands (also referred to as HOSR) in the system (cf. Equation 2.11).

$$HPI_{succ} = \frac{N_{ho-succ}}{N_{ho-events}} \tag{2.11}$$

For the sake of completeness, the definitions for the remaining HPIs, i.e. the HOFR (cf. Equation 2.12) and the PPHOR (cf. Equation 2.13), are given below:

$$HPI_{fail} = \frac{N_{ho-fail}}{N_{ho-events}} \tag{2.12}$$

$$HPI_{ping-pong} = \frac{N_{PP}}{N_{ho-events}} \tag{2.13}$$

For additional, detailed information on the implemented HO procedure [3GP13] and other HPIs the reader is referred to [Jan16, pp. 15]. Also, this concludes the presentation of the four main KPIs.

2.4 Related Work

This section presents the related work corresponding to this thesis. Since two major aspects are considered – the realistic modelling of user movements and behaviours as well as the impact of realistic scenarios on the performance of SON functions – both areas are addressed in the following, respectively.

2.4.1 State of the Art

Mobility Modelling

The performance of a mobile radio network is often evaluated by using Mobility Models (MMs) since one of the key requirements is a seamless movement through the cellular system. Moreover, MMs are crucial and a precondition when testing and assessing the performance of SON functions that rely on HO metrics or individual user data traffic. However, applying new – and untested – features in a live system is often problematic due to uncertainties of executed (radio parameter) changes by SON functions.

Such MMs are usually a simplified (mathematical) attempt to generate a certain reproducible degree of mobility in a system. Regarding that, the well-known random walk MM stands out the most when considering scientific publications from the past

[CBD02]. This MM is easy to implement and an acclaimed reference, especially for 3GPP-like network systems. In addition to that, the European Telecommunications Standards Institute (ETSI) introduced a couple of specified and standardised mobility scenarios when introducing the UMTS standard. Such situations include a so-called Manhattan grid topology where the users walk in the street canyons [ETS97, p. 53]. Furthermore, an indoor office environment was defined to account for movements within buildings [ETS97, pp. 50]. Finally, the mobility of vehicular and pedestrian users is considered in [ETS97, pp. 54]. All MMs defined by ETSI have in common that they follow aim-oriented trajectories, e.g. going from one office to another or walking along a street in the Manhattan grid. However, the underlying environment assumptions are still far away from considering them as *realistic*. For instance, the defined office or Manhattan grid scenarios follow a simplified regular structure. Little to no considerable work includes realistic geographical data. Following this, the authors of [HFB09] present an overview of available tools to generate movements and mobile traffic based on arbitrary motion constraints. What they show is that such constraints are usually simplified network topologies and rarely real (geographical) data.

SON Orchestration and Coordination

The main work so far regarding SON orchestration and coordination was concentrated on three projects funded by the European Union, namely SOCRATES [Kür+10], UniverSelf [Fue+13], and SEMAFOUR [Hah+15b]:

- **SOCRATES:** The SOCRATES project had the primary goal to develop SON functionality for 4G systems. This included all three areas of self-organising use cases, such as self-configuration (see [Kür+10, pp. 109]), self-optimisation (like the LB and RO SON functions presented in section 2.2 or [Dia+10]) and self-healing (cf. [Ami+09]). The developed SON functions acclaimed major recognition in the scientific community and built the basis for many SON use cases that were about to come. Furthermore, first studies regarding the dependencies of multiple SON functions were studied in [Sch+11]. The authors presented a coordination framework and investigated the influences of the (LTE) RO and LB SON functions. In this first step, a simplified 3GPP network scenario was considered.
- **UniverSelf:** UniverSelf developed an Unified Management Framework (UMF) in order to reduce the complexity of future networking systems [Fue+13, pp. 57]. The UMF provides an abstract concept to create and manage mobile network components. This includes SON functionality as well as general Network Empowerment Mechanisms (NEMs). An NEM is an automatic function that solves a

specific problem in the network. The project mostly used simplified 3GPP scenarios to evaluate the UMF or were only of conceptual nature, meaning that they did not test the formulated solutions in complex, large-scale mobile radio networks. Besides the management of the NEMs, the project studied the coordination of different functions as well [Tsa+13].

- **SEMAFOUR:** The objective of SEMAFOUR was to extend the work of its predecessor (SOCRATES) and develop multi-layer and multi-RAT SON functions (for instance the TS SON function described in section 2.2 or). Apart from that, the project did work in the field of Policy-Based SON Management (PBSM), i.e. the management of multiple SON functions running in parallel. For that, SEMAFOUR had a dedicated work package that focused on the coordination and orchestration of diverse (multi-layer, multi-RAT) SON functions. As an outcome, [FLS14a] presents a basic version of PBSM. Some shortcomings, e.g. the absence of context-dependent KPI targets, were addressed later on by the authors of [FLS14b]. Finally, [LSH16] investigated the ability to dynamically improve the SON Function Performance Model (SFPM) based on network measurements. By this, the static (artificial) models, coming from the vendors, adapt to the actual network conditions. Lastly, [Fre16] comprised thorough analyses of (objective-driven) SON operation and SON Objective Manager (SOM) concepts. In the area of SON coordination, the authors of [Iac+15] evaluated methods in a heterogeneous network environment. Moreover, the same authors presented a framework to solve SON conflicts in [Iac+16], even though all evaluations are done here in simplified hexagonal (3GPP) scenarios.

- **Other Research:** The authors of [Ban+11] introduced a policy-based coordination and management concept. This is also the (initial) blueprint for the later PBSM approaches that the SEMAFOUR project used. Furthermore, [SMMT14] developed a coordination method, considering multiple SON functions. However, the evaluation and verification happened only in a hexagonal scenario. The need for SON and SON coordination is also seen for future 5G systems. Therefore, the authors of [Sta+15] presented first conceptual results.

2.4.2 Open Issues and Contributions of this Work

Several issues come to mind when considering realistic mobility modelling. Furthermore, unsolved and remaining problems in the area of SON orchestration and coordination are the following (please note that, in reference to Figure 1.5, each issue is also marked with a green labelled circle in Figure 2.16):

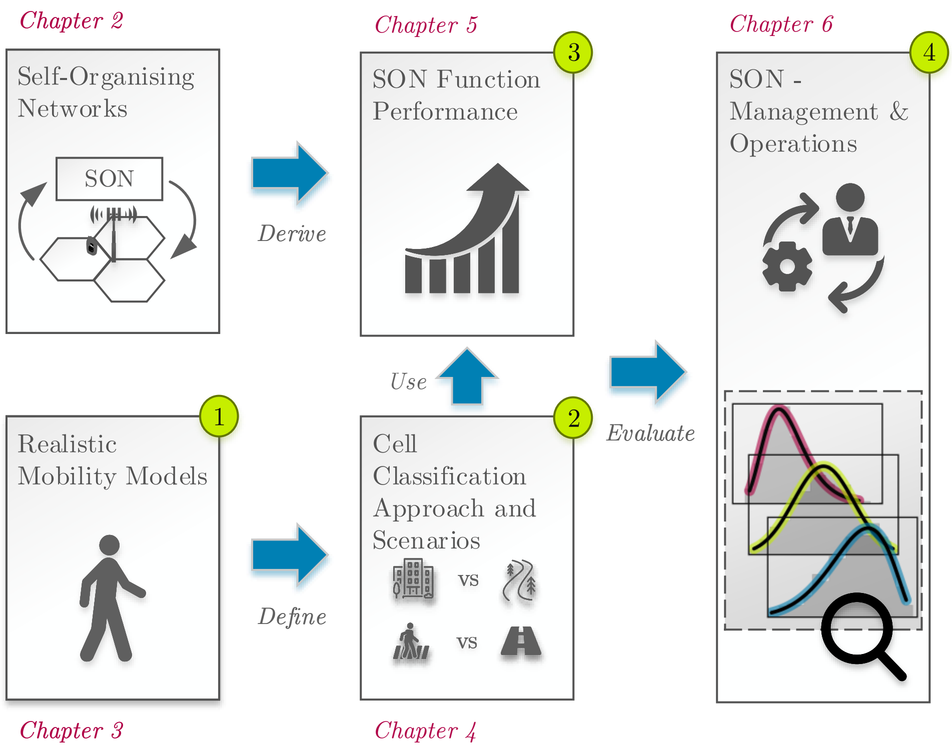


Figure 2.16: Methodology, structure (compare also Figure 1.5) and issues that shall be solved in this thesis

1. How can MMs come closer toward the movements in the real world? For that, several MMs are used or developed by including real(istic) geographical data. Each MM is typically focusing on one specific aspect, e.g. users within buildings [Ros+13b], pedestrians [Hah+15c], vehicular users [Kra+12] or even a public transportation system [Hah+16]. These models are explored by summarising the basic approaches to generate the aforementioned movements.

   What is the actual impact of different models, each addressing various behavioural and motion aspects, on the network functioning? When considering HO related performance indicators such as the HO success or failure ratio, differences might arise that are due to the velocity, degree of stationarity, etc. Moreover, what are the implications when considering the testing (and approving) of SON functionality for an MNO?

   These issues will be addressed and evaluated in chapter 3. Moreover, a majority of the applied and generated mobility trajectories are made publicly available and are ready to use (see [Ros+13c]). By this, the scientific community is encouraged to use more realistic simulation scenarios that rely on a) these advanced mobility models and b) (realistic) network deployments to evaluate futuristic mobile radio system solutions.

2 What are the means to make a large-scale mobile radio network manageable? An MNO might has to operate thousands of cells in the network. To (re-)configure all of them is highly complicated to do manually. A classification method seems to be a natural solution to answer this question. This approach will be addressed in chapter 4.

3 In light of the open issues coming from the mobility modelling, how are different SON functions, each changing different (radio) parameters, performing in a realistic environment? For that, chapter 5 investigates three SON functions in three distinct network scenarios.

4 After gaining a greater understanding of how SON functions *behave* in changing environments (see point 3), the question remains whether SON can be used at all to steer the network towards a dedicated KPI direction. Before that, the question is if SONs are actually capable of altering the system performance and, if so, how far can the performance be changed?

Finally, the impact of different SON combinations on the network performance needs to be known. This is of utmost importance when it comes to a (policy-based) management approach as described in [Fre16]. For that, the question is how different SON functions change and impact the network performance with varying (SON function) combinations?

These questions will be addressed in the first part and second half of chapter 6.

To sum up, this thesis focuses on investigations about the performance and manageability of SON functions in realistic scenarios to alter the network performance. By that, it paves the way for future self-management frameworks that might incorporate cognitive functions in 5G systems. This is done by providing reasons why the handling of SON in (large-scale) mobile networks needs to happen with caution.

Chapter 3

Advanced Mobility Modelling

As already mentioned in chapter 2, the focus of this thesis lies on realistic microscopic system-level simulations. For that, Mobility Models (MMs) are needed featuring not only a realistic movement (e.g. walking along a street) but also a rational behaviour (e.g. waiting at traffic lights). Figure 3.1 shows a snap-shot of a reasonable user mobility mix in a large-scale network scenario. Besides the two RATs (LTE and WiFi) as well as the two cell layers (macro and small cells), this scenario features vehicular and highway users, pedestrians, trams as well as railways. Black lines indicate established connections between the UEs and cells by the HO algorithm. All these MMs are described and evaluated regarding Handover Performance Indicators (HPIs) later on.

Now, a general question remains: Why should realistic mobility models be considered in the first place. One case of application lies in the usage and testing of SON functionalities because an MNO wants to operate its network as efficiently as possible. Yet, MNOs are often reluctant when it comes to applying (new) SON functionality in the live network operation due to sudden parameter changes or unforeseen system dependencies. Therefore, it is always crucial to have a thorough analysis and understanding of the impact of such SON algorithms on the mobile network beforehand. Consequently, these studies are only doable by using simulations (and not a real system) to get sophisticated statements about the performance that the operator approves. However, these testings are hardly achievable by using a standardised hexagonal network layout in combination with uniformly dropped users [3GP10], which does not reflect a real mobile radio system. So the simulation assumptions should be as realistic as possible in all imaginable aspects to gain the trust of MNOs.

These assumptions, of course, also include the modelling of mobility in a network, since some SON functions rely on KPIs coming from individual users. For example, an HO optimisation (e.g. Robustness Optimisation (RO) [Jan+10]) function needs HO counters and a load balancing algorithm (for instance the used LB [Lob+10] and TS

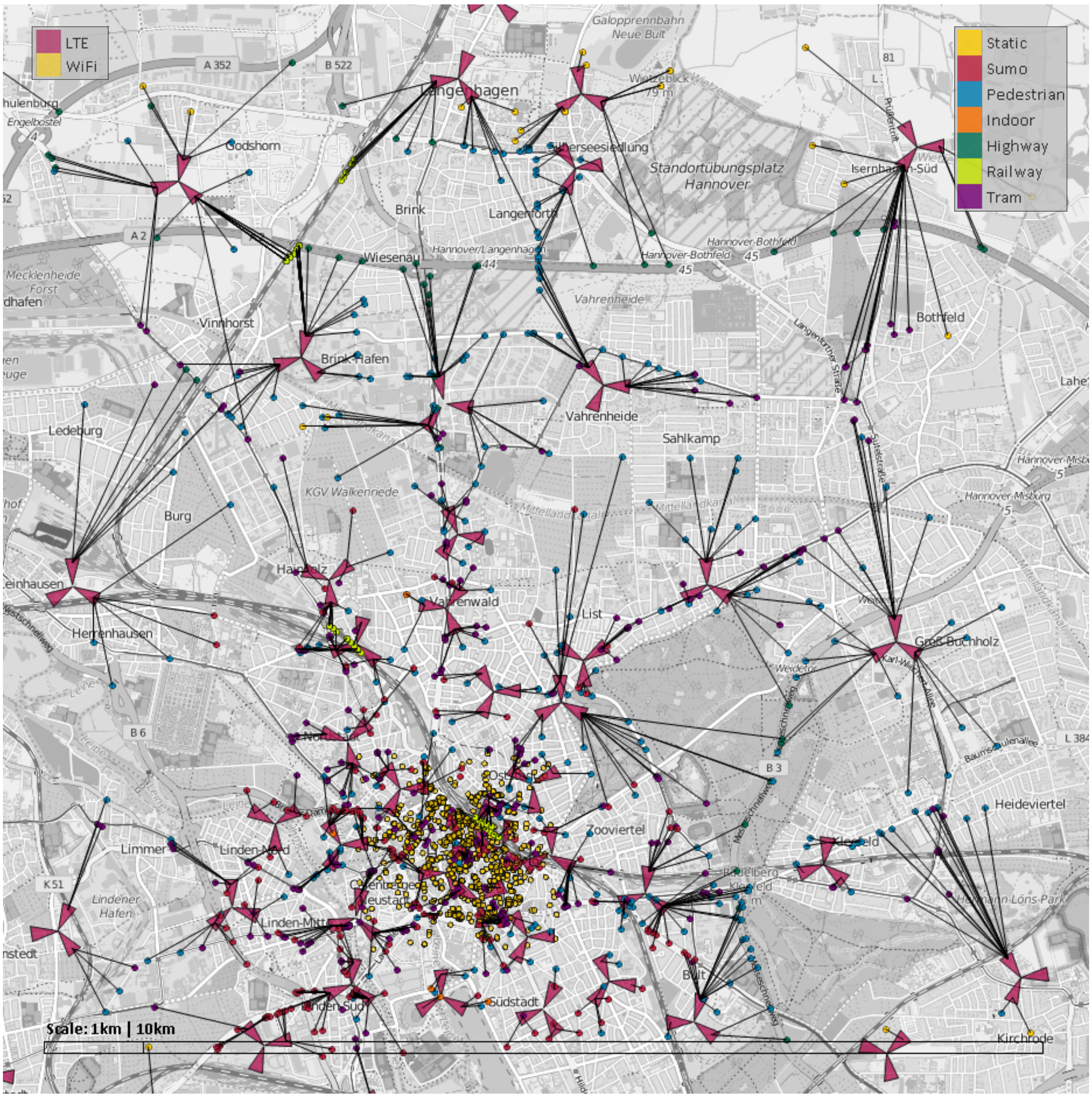


Figure 3.1: Scenario with different user mobility classes covering an area of 100 km^2 in the “Urban Hannover Scenario”

functions [Wil+16]) relies on particular user load information. Unfortunately, those KPIs are often evaluated by using simplified mathematical descriptions that generate and simulate the user directions and velocities. A well-known example is the random walk MMs [CBD02]. Other MMs from the literature expand such numerical descriptions to bring these (random) movements somehow closer towards a realistic behaviour [PS06], such as by going along a so-called Manhattan grid, following specific reference points as a group or avoiding obstacles. Yet, it is still an open issue if different degrees of realism concerning user movements and behaviours have an impact on the Handover Performance (HP) and, thus, the overall KPIs or not. To clarify this (HP) issue, consider the following: The HO algorithm that ensures the connectivity between users and the mobile network has to cope with all kinds of mobility in an appropriate way. This means that the (HO) operating point of the cells in the network, consisting of a HYS and TTT value pairs, should be well adjusted. These operating points might be different for each cell in the network. For instance, highway cells need to quickly hand over the users due to high velocities, whereas (deep) urban cells can have higher HYS and TTT values to prevent unnecessary PPs. To account for these various kinds of movements, respective MMs are needed eventually. Furthermore, these MMs might impact the KPIs considerably, and by that, also the performance of SON functions. These points have been (partially) addressed by two European funded projects, namely SOCRATES [Kür+10] and SEMAFOUR [Hah+15b]. Each dealt with SON functions and the management of SON-enabled mobile networks using heterogeneous scenario settings – already including realistic mobility modelling based on real geographical data. On top of that, the projects redefined and further developed new MMs.

In short, the question remains whether (realistic) mobility modelling has profound implications on the simulated network performance or not. Thus, this chapter investigates the effects of *realistic* mobility modelling on the network performance. As a reference, the random walk MM is always considered. For that, the organisation of the remaining sections is as follows: In section 3.1, an overview regarding the state of the art on mobility modelling is given. After that, section 3.2 describes the simulation scenario and presents the results featuring three main HPIs. Finally, section 3.3 summarises the major scientific findings.

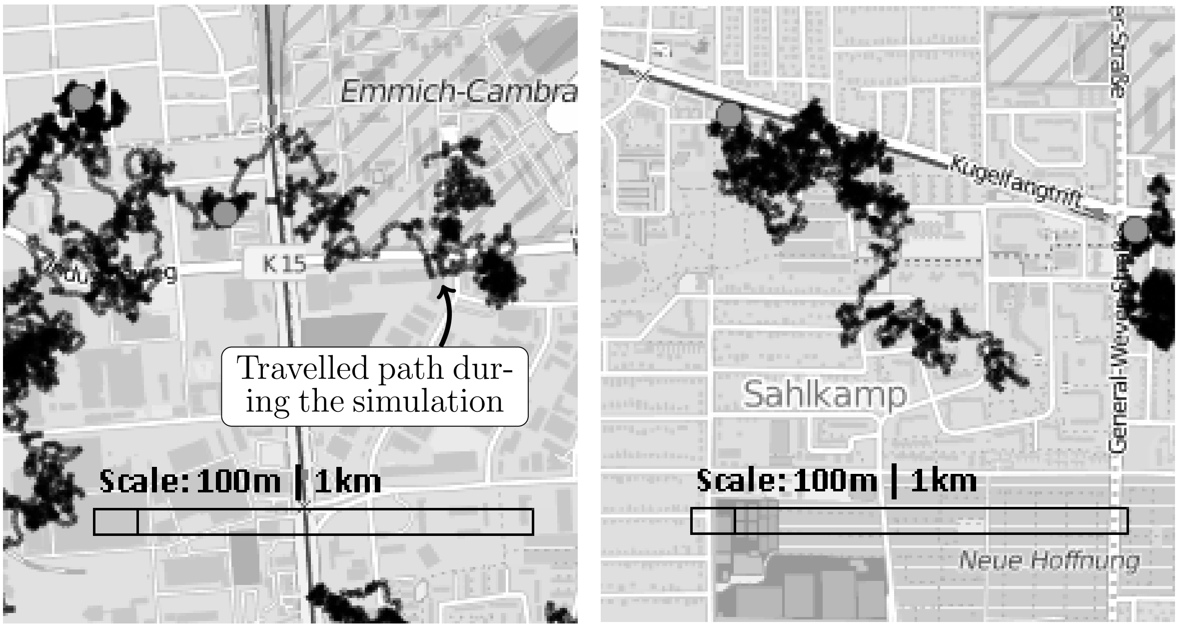
Parts of the work presented subsequently have been published before in [Ros+13b], [Hah+15c] and [Hah+16]. Especially, the handover performance analysis presented in section 3.2 have been performed by Dennis M. Rose, Institut für Nachrichtentechnik, TU Braunschweig in close collaboration with the author. Whereas Mr Rose focuses on the underlying simulation methods and capabilities, i.e. the structured repository of user traces, the generation of highly complex scenarios and the simulation of such, the author's interest remains on mobility modelling and the impact on the performance of realistic network scenarios.

3.1 Mobility Models

This section outlines the state of the art on (advanced) mobility modelling. Much work has been done to bring realistic motion patterns, as well as behaviour, into link- and system-level simulations. These MMs are presented below by giving brief explanations. Also, well-known (mathematical) MMs from the literature (e.g. [CBD02] and [CGPEG11]) – the random walk and random waypoint MM – are recapitulated.

3.1.1 Random Walk/Waypoint Mobility

Using models that can be expressed by simple mathematical equations is one of the easiest ways to simulate user mobility in a network scenario. One example is the so-called *random walk* MM, where the direction and distance to "walk" are chosen haphazardly. A simple extension of the random *walk* model is the random *waypoint* MM. In addition to the mobility itself, the model includes a period of time where the user stands still. The time until the user walks on can also be set randomly [CBD02]. Figure 3.2 show random walk paths in the scenario. The users are usually dropped arbitrarily over the entire simulation scenario and proceed to walk at a predefined velocity. One can see that the movements do not follow dedicated streets or paths and that users can also walk "through" buildings. In the following, this thesis considers velocities ranging from 5 to 50 km/h.

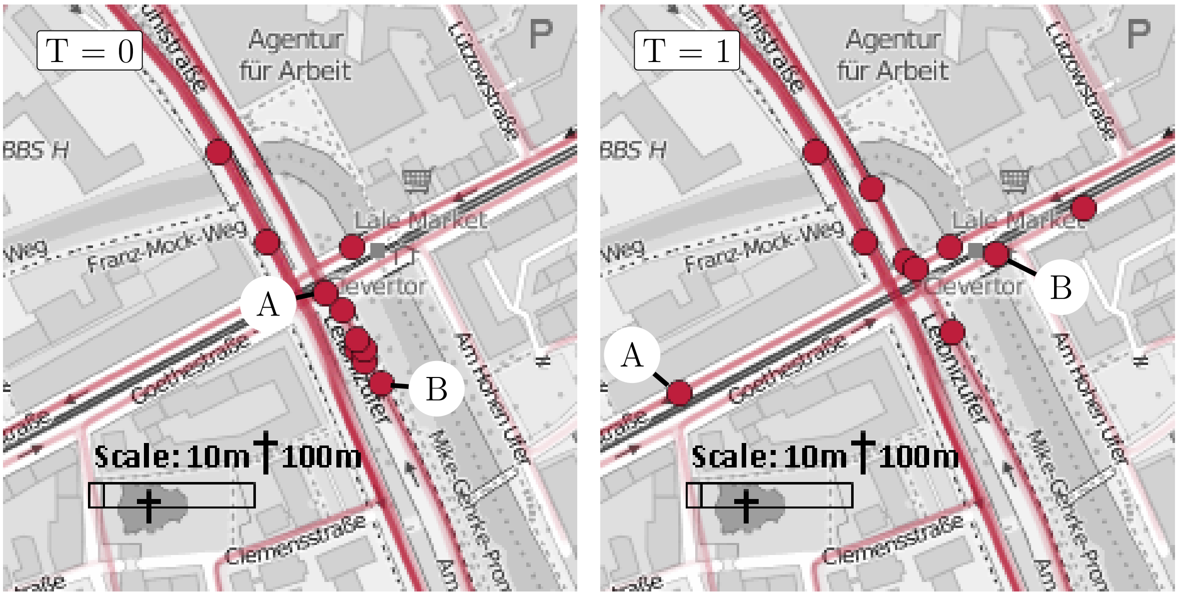


(a) Example 1 **(b)** Example 2

Figure 3.2: Random walk mobility. Please note that the total simulated paths of the users are indicated by the black lines and the respective positions are symbolised by the grey dots. The same applies for the following figures.

3.1.2 Vehicular Mobility

Vehicular traffic mostly follows the street layout of a given city. The open source software Simulator of Urban Mobility (SUMO), developed by the German Aerospace Agency (DLR) [Kra+12], can be used to model this. With SUMO it is possible to simulate (urban) mobility on streets with all its facets. This includes, for example, the queuing in front of traffic lights, the changing of street lanes or the overtaking manoeuvre of other vehicles. As an example, Figure 3.3a shows users (two of them are labelled with “A” and “B”) waiting at a traffic light. The red lines represent the routes/trajectories of the users. In Figure 3.3b they proceed to move on. Additionally, it is observable that the users only travel on streets. For that, so-called turning probabilities for each street intersection have to be defined manually for the given simulation scenario, which usually turns out to be a very time-consuming task. If this is given, SUMO uses an Origin/Destination (O/D) matrix to spawn users and generate the respective routes. Available scenarios that are ready to use and a detailed description of how to handle SUMO can also be found in [Deu].



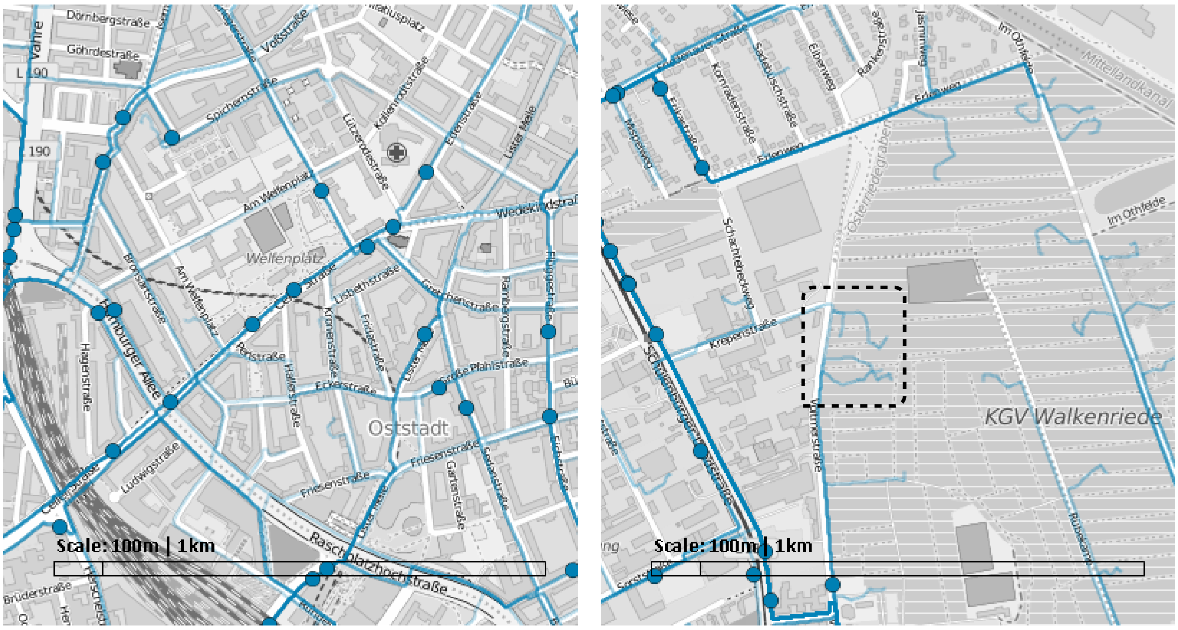
(a) Queuing up in front of a traffic light **(b)** Same vehicles processing to driving on

Figure 3.3: Vehicular mobility (red lines and dots)

3.1.3 Pedestrian Mobility

By using real geographical data the authors of [Hah+15c] have developed a realistic pedestrian MM. In contrast to the SUMO users, pedestrians also move through parks, cross streets and use pavements. Examples of the resulting trajectories are given in

Figure 3.4. The generation relies on real(istic) geographical data (e.g. OpenStreetMap (OSM) data [HW08]), including 2D building information, paths and ways as well as street data. Given the building information, pavements surrounding such buildings can be generated and used for the routeing through the network. The routeing here starts and ends at building entries and is based on the well-known Dijkstra algorithm [Cor+01, pp. 658]. Please note that the greatest difference compared to SUMO is that pedestrians walk more slowly and also use ways that are not suitable for vehicles. For instance in a park, shown as a dashed rectangle in Figure 3.4b.



(a) Walking in the city centre **(b)** Walking through a park

Figure 3.4: Pedestrian mobility (blue lines and dots)

3.1.4 Indoor Mobility

The authors of [Ros+13b] propose a MM to account for characteristics of indoor users. Such characteristics include different aspects: For example, the times of stationary (where users do not move but stand still in the room), the changing of rooms in a realistic way (i.e. moving through doors) or different activity profiles based on the building type the user is currently in (i.e. office or living apartment buildings). The change between a state (for instance moving from the *"living room"* to the *"kitchen"*) is modelled with a (Markov) jump process [ASHS10]. An actual movement from one state to another (i.e. the respective rooms in a building) is also realised in a realistic way by considering doors, hallways, and room interior. Since full 3D building data (including inner layouts with walls and doors) is by and large not commonly available and often rather expensive, the authors of [HRK14a] and [RHK14] have suggested a method to generate 3D buildings based on simple 2D shapes. Exemplary indoor users are shown in Figure 3.5, along with their paths inside the buildings.

(a) Users inside an industrial building **(b)** Users inside an office-like building

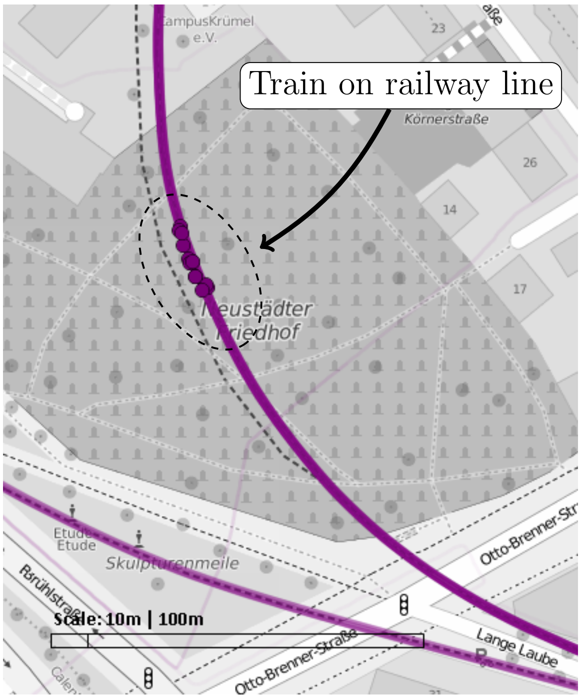
Figure 3.5: Indoor mobility (orange lines and dots)

3.1.5 Group/Correlated Mobility

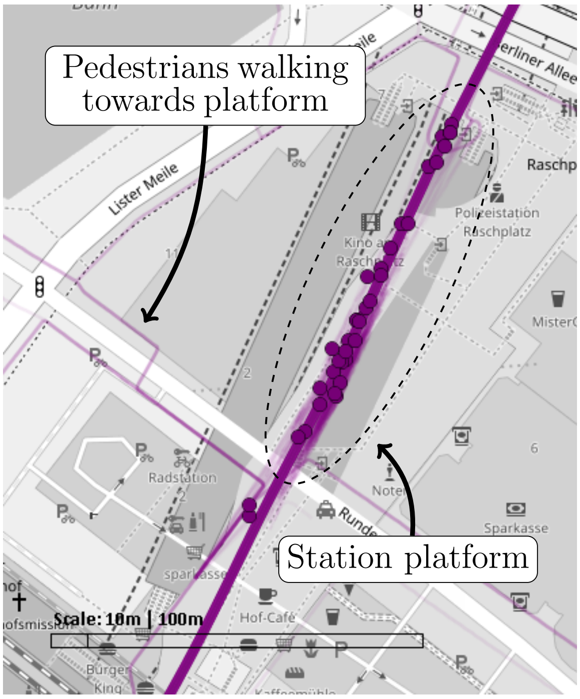
Two realistic MMs have been combined for the first time in a bachelor thesis[1] and later on in [Hah+16]. Here, the pedestrian MM (cf. subsection 3.1.3) and a new MM that mimics a public transportation system (e.g. bus or metro lines) work jointly. At first, pedestrians walk, as described previously, from a building entry towards the nearest station platform. After that, a waiting phase is included on the respective platforms. The pedestrians are either walking about or are standing still here. When the train

[1] C. Herold, "Entwicklung und Implementierung einer realistischen Straßenbahnmobilitätsmodells", Bachelorarbeit, Technische Universität Braunschweig, Institut für Nachrichtentechnik, Ba. 15/703, 2015

has arrived, the users enter the train and move towards an allocated seat. At the final station, the users leave the train and proceed to walk towards the desired building entry. This model integrates a real time table and the changing of a transportation line, too. Figure 3.6a shows a moving train on a tram line. In Figure 3.6b, many pedestrians are waiting at a station platform for the next tram, as well as pedestrians walking towards the next station platforms.



(a) Train travelling in the scenario

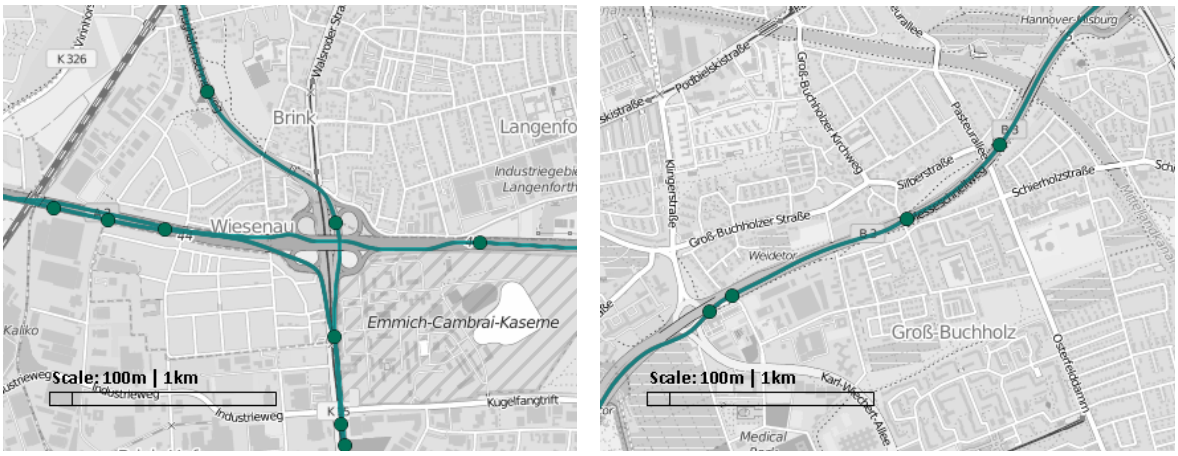


(b) Passengers waiting for the next train

Figure 3.6: Group/Correlated mobility (purple lines and dots)

3.1.6 Highway Mobility

Last of all, we have developed an entirely new MM that accounts for high-speed users travelling on, e.g., motorways or highways. The needed user trajectories can be produced by using real geographical data, provided by official sources, such as land registry offices or open source initiatives, like the OSM project [Ope]. If the appropriate data sources are available, the routes can be selected manually. Finally, by interpolation, a predetermined velocity can be specified. Figure 3.7 shows examples of users travelling on motorways. Please note that no advanced mobility aspects such as traffic jams or overtaking manoeuvres are implemented as they can be found when using, e.g., SUMO. The main drawback of SUMO is that the scenario generation and setup are very time-consuming. On the other hand, the number of highways and direction changes of subscribers is limited. Thus, the main benefit of using this MM is the reduced trace generation time that comes with a slight drawback of mobility features (overtaking, lane changes, etc.).



(a) Vehicles on the highway "A2" **(b)** Vehicles on the "Messeschnellweg"

Figure 3.7: Highway mobility (green lines and dots)

3.2 Impact on the Network Performance in Realistic Network Scenarios

In order to evaluate the impact of the various MMs on the actual network performance, the Handover Performance (HP) will be further investigated as an example. Therefore, multiple combinations of HYS and TTT values are simulated. HYS defines the margin between the RSS of a potential (new) target cell and the source cell. The TTT is the time this potential target cell has to fulfil the margin until the HO command is triggered. The actual values of HYS and TTT are mostly in line with specifications from 3GPP (the values are rounded to 100 ms due to the temporal resolution of the simulator) and listed in Equation 3.1 (in [dB]) and in Equation 3.2 (in [sec]) [3GP13]. Hence, to account for all possible combinations (i.e. a simulation with each of the eleven HYS and eleven TTT value pairs), 121 simulations are needed for every MM.

$$HYS \in \{0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10\} \tag{3.1}$$

$$TTT \in \{0.0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 1.0, 1.2, 2.5, 5.1\} \tag{3.2}$$

The actual HO analysis is done by evaluating three HPIs, namely the Handover Success Ratio (HOSR), the Handover Failure Ratio (HOFR), and the Ping-Pong Handover Ratio (PPHOR). Note that the Radio-Link-Failure Ratio (RLFR) is part of a later analysis in this chapter. For that, the total number of HO events (N_{events}) is needed. $N_{HO-events}$ are defined by the sum of all HOs (which includes all non-PPs *and* all PPs), HOF and RLF events (see Equation 3.3) that occur during the simulation time. Please note that the KPIs used here differ from the ones defined in subsection 2.3.4 by focusing on the total accumulation. Hence, the ratios are based on the performance results for the whole simulation time of 30 minutes.

$$N_{ho-events} = \sum HO + \sum HOF + \sum RLF \tag{3.3}$$

The respective events are defined as follows: a HO event is a successfully executed HO command. If during the actual HO execution the user SINR is too bad in the source cell or the target cell, the HO fails and is counted as an HOF. In contrast to an HOF, which only happens during an actual HO execution, RLFs can be experienced if the user loses the signal or if the user SINR falls below a -6.5 dB threshold [3GP15].

Now, the HOSR ($HPI_{success}$) can be calculated by dividing the total number of HO events by $N_{ho-events}$. See Equation 3.4:

$$HPI_{success} = \frac{\sum HO}{N_{ho-events}} \tag{3.4}$$

The HOFR ($HPI_{failure}$) is defined by dividing the total number of HOF events by $N_{ho-events}$. See Equation 3.5:

$$HPI_{failure} = \frac{\sum HOF}{N_{ho-events}} \tag{3.5}$$

The RLFR (HPI_{RLF}) is defined by dividing the total number of RLF events by $N_{ho-events}$. See Equation 3.6:

$$HPI_{RLF} = \frac{\sum RLF}{N_{ho-events}} \tag{3.6}$$

At last, the PPHOR ($HPI_{ping-pong}$) is defined by dividing the total number of PP events by $N_{ho-events}$. See Equation 3.7:

$$HPI_{ping-pong} = \frac{\sum PP}{N_{ho-events}} \tag{3.7}$$

The time until a successful HO is counted as PP (T_{pp}), i.e. the user re-connects to the old source cell and potentially making the first HO unnecessary in the first place, is defined by Equation 3.8. t_{min} herein is set at five seconds.

$$T_{pp} = 2 * (TTT + t_{min}) \tag{3.8}$$

In total six MMs are considered, that is: SUMO (cf. subsection 3.1.2, also referred to as "vehicular"), the pedestrian MM (cf. subsection 3.1.3), the indoor MM (cf. subsection 3.1.4), the group MM (cf. subsection 3.1.5), the highway MM (cf. subsection 3.1.6), and the random walk MM as a reference (cf. subsection 3.1.1). The simulation time is set at 30 minutes with a temporal resolution of 100 ms. The required path loss information, with a spacial resolution of 1 m × 1 m, are predicted by using a 3D ray-tracing tool [Kür99], [KM02]. To account for a reasonable interference level, 50 % of the transmit power (i.e. 43 dBm) is used to calculate the resulting user SINR values. All scenario and simulation parameters are further specified in Table 3.1.

Table 3.1: Scenario and simulation parameters for the HP investigations

Parameter	**Value**
Simulation area	10 km × 10 km
RAT	LTE
Network layer	Macro cells
Frequency	1800 MHz
Bandwidth	10 MHz
Transmit power	46 dBm
Interfering power	43 dBm
Antenna gain	17 dBi
Path loss prediction model	3D ray-optical (see [Kür99] and [KM02])
Spatial resolution	1 m × 1 m
Number of users	1000 (per mobility model)
Simulation time	30 min
Temporal resolution	100 ms

3.2.1 Handover Success Ratio

The results regarding the HOSR (also referred to as $HPI_{success}$) are shown in Figure 3.8. A general observation is that for low HYS and TTT values the HOSR is the highest in all cases. In contrast, the higher the value pairs get, the lower the HOSR will be. This is an expected result, since high HYS and TTT values cause a late HO command. This increases the probability of *negative* HO events, such as HOFs or RLFs. However, with a closer examination of the six MMs variations in the HOSR performances can be seen. For example, the group MM and highway MM (see Figure 3.8e and Figure 3.8f) feature a faster drop of the HOSR regarding higher HYS and TTT values compared to the random walk MM (see Figure 3.8a). This is explainable by considering the velocities of the users for the respective MMs. Of course users on the highway travel with a higher speed. This also means that the RSS conditions tend to vary drastically, which also includes a quick leaving of the connected cell that increases the probability of HOF and RLF events. The same holds true for the group mobility. In a (deep) urban environment the inter-site distances are usually small. Hence, users enter and leave cells quickly. In combination with faster moving public transportation systems, similar effects compared to the highway users are observable. The HOSR of pedestrians and indoor users (see Figure 3.8c and Figure 3.8d) tend to be less affected by TTT values in comparison to the other MMs. The authors of [Hah+15c] also compared the pedestrian MM with the traditional random walk MM. Both MMs feature a similar behaviour, but the random walk users exhibit greater outliers when it comes to the minimum and maximum amount of total HO per cell. The results shown here are also in line with the analysis published in [Ros+13b]. The indoor users (that move through buildings in a realistic way by considering doors and hallways) have been compared with random walk users inside buildings, which do not consider the internal environment of a building and thus walk through walls. Also, this can be explained with the rather low velocity of pedestrians and indoor users. Due to the short distances covered by a user within a given time, the signal conditions also vary only a little.

At first glance, the results of the realistic MMs (see (b) to (f) in Figure 3.8) do not seem to be drastically different compared to the random walk mobility (cf. Figure 3.8a). However, this changes when considering the following HPIs.

3.2.2 Handover Failure Ratio

The HOFRs (i.e. $HPI_{failure}$) for the six MMs and all HYS-TTT value pairs are shown in Figure 3.9. One general trend for all MMs is noticeable: the HOFR is increasing

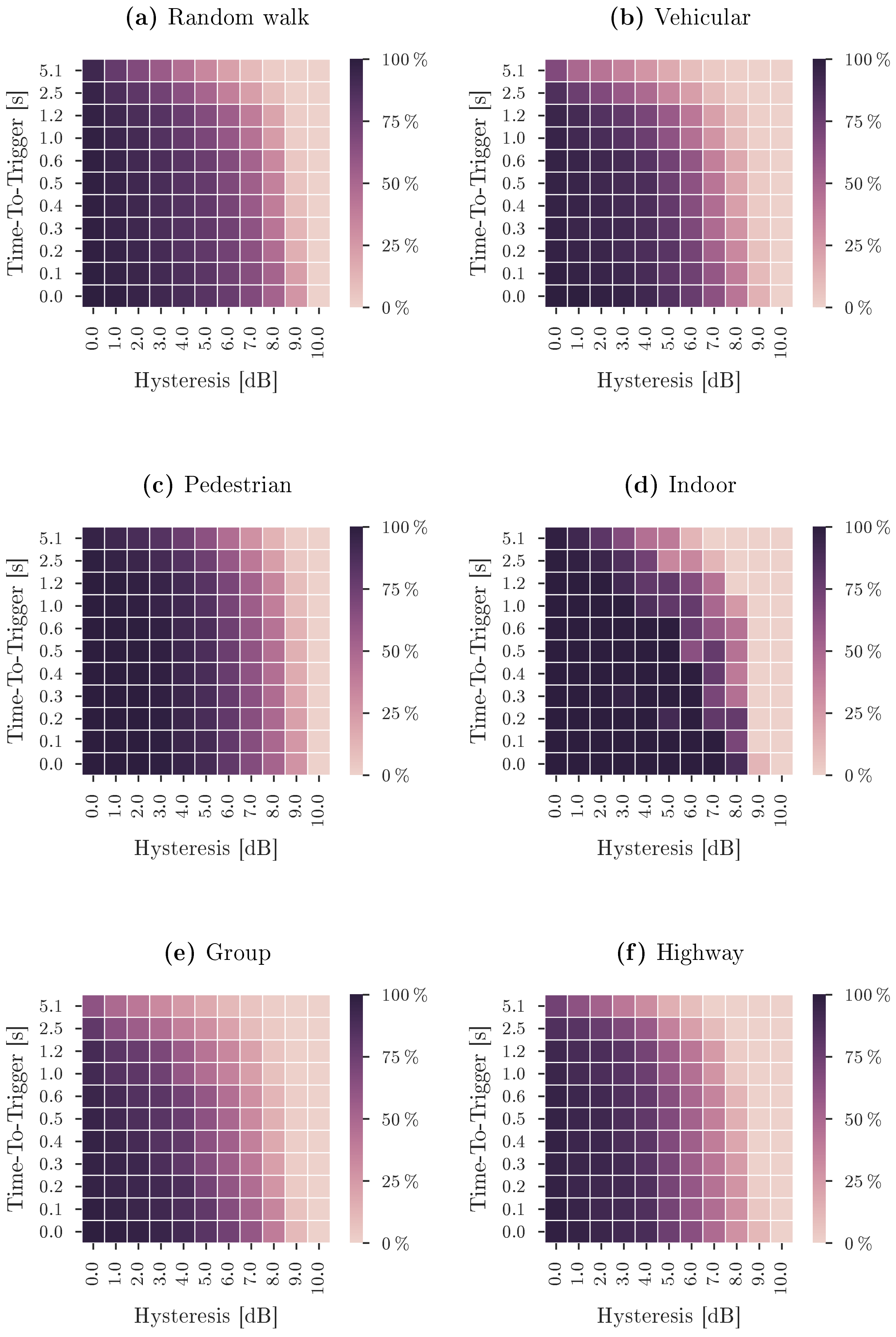


Figure 3.8: HOSR for different mobility models

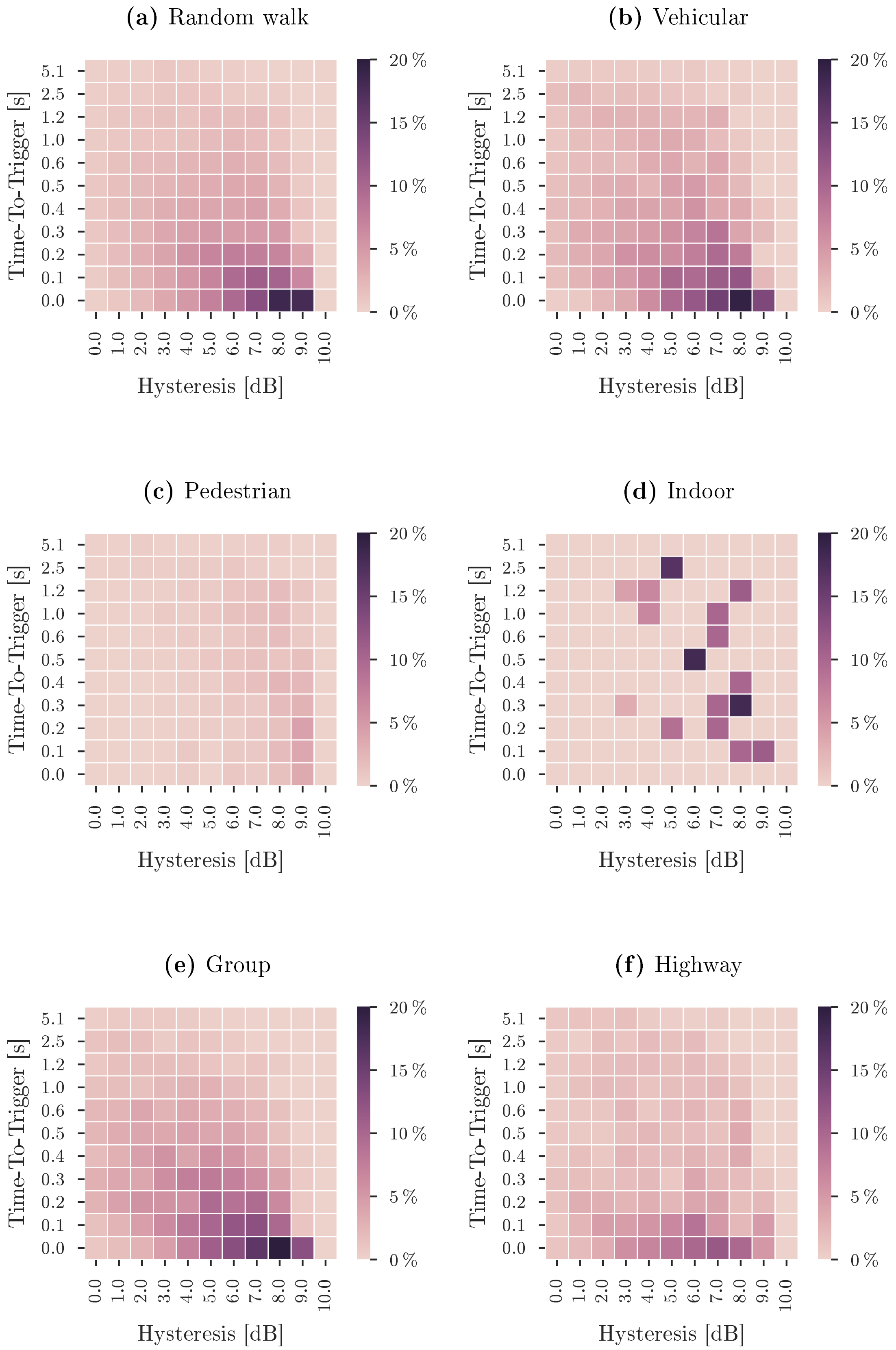


Figure 3.9: HOFR for different mobility models

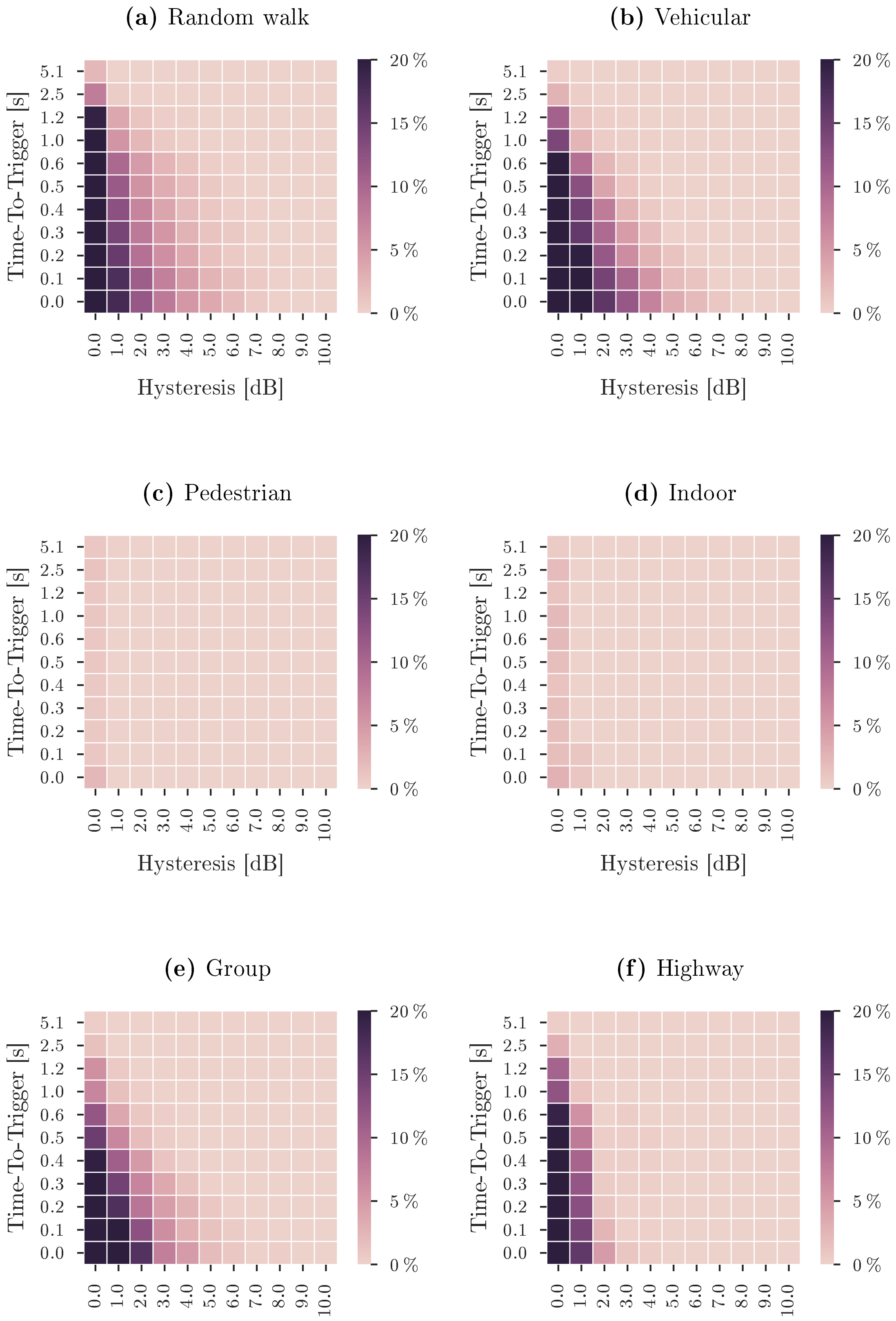


Figure 3.10: PPHOR for different mobility models

if the TTT gets lower and the HYS higher. This is an expected result because high HYS values mean a late HO command. Meaning that the users are already deep in a different cell so that the interferer dominates the serving cell. The consequences are bad SINR values, which increase the probability of HOF events. Another fact featured in all results is the total absence of HOF events at 10 dB HYS. In the simulations, no HO will occur any more because the HO command simply comes too late and hence the user will experience an RLF event. Yet, similar to the HOSR, distinct varieties are observable. At first, the HOFR for pedestrians and high-speed users (see Figure 3.8c and Figure 3.9f) are lower compared to the other MMs. Considering pedestrians, the reason is the prevailing good HOSR performance. Only a few users will experience HOF events at all because of the modest changes of the RSS conditions. On the other hand, highway users have a worse HO success performance, because, due to the speed of the users, an RLF event will happen before an HO situation could be detected and the corresponding HO command can be triggered. Indoor users (see Figure 3.9d) feature a slightly different behaviour compared to the remaining MMs. With higher HYS and lower TTT values, the ratio of HOF increases, but not as smoothly as for the other MMs. This behaviour can be traced back by looking at the generated movements of the indoor users themselves (see in subsection 3.1.4 with Figure 3.5 and [Ros+13b]). Users move only inside buildings and in a realistic way. This is ensured by using doors, hallways, and elevators to reach other stories. With this, the RSS conditions might change drastically because all of the sudden one or more walls are between the cell and the receiver (i.e. the user). If in a particular building users often move from one part to another of the building, HOF might occur every time a user enters the hallway or a specific room. By this, the noteworthy HOF behaviour is observable in Figure 3.9d. The two remaining MMs, vehicular users (i.e. SUMO) in (b) and the group mobility in (e), feature a similar behaviour compared to the acclaimed random walk users (see (a) in Figure 3.9). However, especially SUMO was used to evaluate the impact of SON functions on the network. The overall gain of SON usually is lower if a realistic network topology is considered, rather than a hexagonal scenario with users following a random walk mobility pattern. This is due to the aim-oriented nature of the trajectories, which start at a certain place, follow a distinct path (such as streets or motorways) and end at a certain location. Random walk users, on the other hand, do not feature these characteristics. For a detailed comparison of two well-known SON functions in different network environments, the reader is referred to [Lob+10] or [Jan+10].

This HPI details greater differences of the respective MMs in terms of the HOF behaviour in comparison to the previous one (i.e. HOSR). Each MM tends to produce a unique HOFR performance compared to the random walk MM. The next subsection shows even more differences in the results between the different MMs.

3.2.3 Ping-Pong Handover Ratio

Finally, the results for the PPHOR (i.e. $HPI_{ping-pong}$) can be found in Figure 3.10. A predominant trend is noticeable: with increasing HYS or TTT values the ratio of PP decreases, which is also an expected result because, with 0 dB HYS and 0 s TTT, the users always connect to the best server (i.e. the transmitter with the highest received power). This can also result in a lot of HO commands in a short period and, thus, lead to a high PPHOR. Once again, noticeable differences can be seen for the different MMs. The pedestrians and indoor users (see Figure 3.10c and Figure 3.10d) feature a lower PPHOR in comparison to the other MMs. This is due to the slow, but aim-oriented movements of the users simulated with these MMs, resulting in a decreased probability that a PP event will occur.

(a) Simplified hexagonal topology based on [3GP10]

(b) Realistic heterogenous topology based on [Ros+16a]

Figure 3.11: Two sections of the BSMs for different network topologies

The vehicular and group mobility users (see Figure 3.10b and Figure 3.10e) feature higher PPHORs for increasing HYS values compared to the random walk users (Figure 3.10a), because the faster aim-oriented movements lead to a greater deterioration of RSS conditions. Even though highway users feature an aim-oriented mobility profile as well, the PPHOR is less affected by HYS values. However, a noticeable ratio of PP events can be still seen for low HYS values (0 dB and 1 dB) and for TTT values up to

1 sec. Figure 3.11 gives an explanation for this behaviour by depicting two best server maps (different cell areas are shown with varying colours, also compare section 2.1) – for a hexagonal and the realistic topology, respectively. Also, the sector sites are represented by red triangles. One can see that in Figure 3.11b the cell borders are scattered. This means that the cell edges are not "sharp" and not clearly distinguishable as in a traditional hexagonal topology. If a low HO decision point is chosen (i.e. low HYS and TTT values), the user will connect to the best server as soon as the cell is entered, hence producing a lot of PP events.

Once again, the various MMs lead to a different HO behaviour. Each MM influences the HYS and TTT performances in a reasonable way and thus result in a remarkably different behaviour compared to the well-known random walk MM.

3.2.4 Overall Handover Performance

Now, after investigating the different MMs separately, this section introduces a realistic mobility mix. This mix consists of traces of all five *realistic* MMs that have been presented here. To compare both mobility mixes, an HP metric is used that considers all negative HPIs. These include the HOFR (see Equation 3.5), the PPHOR (see Equation 3.7) as well as the RLFR (see Equation 3.6). All HPIs are combined and weighted (w) as shown in Equation 3.9.

$$\begin{aligned} HP = & \frac{w_{failure} \cdot HPI_{failure}}{w_{failure} + w_{ping-pong} + w_{RLF}} \\ & + \frac{w_{ping-pong} \cdot HPI_{ping-pong}}{w_{failure} + w_{ping-pong} + w_{RLF}} \\ & + \frac{w_{RLF} \cdot HPI_{RLF}}{w_{failure} + w_{ping-pong} + w_{RLF}} \end{aligned} \tag{3.9}$$

The operator might set an HO policy to $w_{RLF} = 2$, $w_{failure} = 1$ and $w_{ping\text{-}pong} = 0.5$. This means that the RLFs shall be reduced and the HOFs avoided. PPs are tolerated as side effects of the RLF reduction. Both, the weightings used and Equation 3.9, are also in line with [Bal+11].

Figure 3.12 presents the simulation results. The left displays the outcome when simulating random walk movements only. The right side features results from the realistic mobility mix. Apart from the overall HP, shown in the top row of Figure 3.12, the performances for two exemplary cells in the scenario are presented (cf. middle and lower row of Figure 3.12). The locations of the exemplary cells feature two environments: the location of cell 1 is in a rural area serving mostly pedestrians, cell 2 is covering a

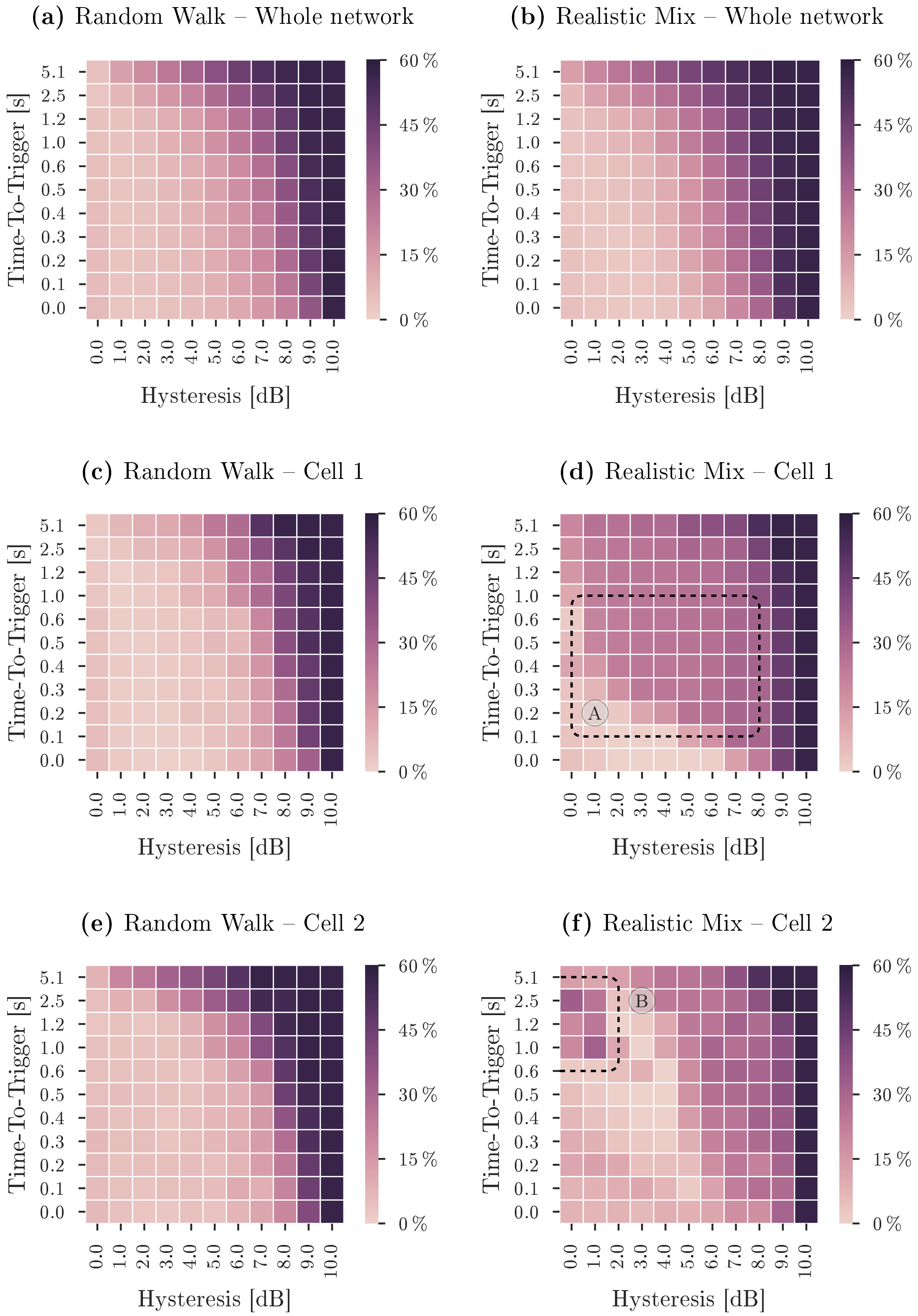


Figure 3.12: HP for a random walk model and a realistic mobility mix

(deep) urban area near a train station with vehicular and group users. Note that the lower the values in the figures, the better the performance. When considering the overall HP, the difference between a system with a traditional random walk MM compared to a realistic mobility mix are not clearly visible (see Figure 3.12a and Figure 3.12b). This is due to the greater number of cells in the system and the different behavioural aspects of each realistic MM. In the end, the performance gets averaged and comes close to the nature of a random walk MM. However, comparing the performance of individual cells against each other, greater differences can be seen in case a realistic mobility mix is considered (cf. right side of Figure 3.12). Figure 3.12d and Figure 3.12f feature unique behaviours between both mobility mixes, which now include HYS-TTT value pair performances that differ considerably. See for example the higher performance values marked with "A" and "B", that feature different HYS-TTT combinations compared to Figure 3.12c and Figure 3.12e. These variations are due to the different degrees of mobility that the cells experience. On the other hand, the random walk MM (cf. left side of Figure 3.12) leads to very similar HPs, even if individual cells are considered.

These results show that realistic MMs can cause unique HPs on a cell level, whereas the random walk MM tends to produce similar results throughout the scenario. This is a valuable finding when it comes to setting the assumptions of, e.g., SON simulations and testing different algorithms for a network operator.

3.2.5 Other Key Performance Indicators

The previous subsections analysed the HP on the assumption of a constant interference level (i.e. 50 % load for each cell in the scenario) to reduce the complexity of the system and to account for a rational utilisation of the network. However, as soon as a (simple) data traffic model is applied and the users produce an individual data request, the cell load shows an entirely different behaviour ([VDL09] provides additional information on how the cell load calculation is done here). For example, if a train (or a public mass service vehicle as described in subsection 3.1.5 and [Hah+16]) is leaving a source cell, the interference conditions get worse for all the users on that train, and thus more resources are needed to satisfy the (constant) data rate requirements. This leads to so-called "spikes" in the cell load profile. Such *mass* HOs behaviour, i.e. an accumulation of a lot of HO commands at the same time and location, can usually not be simulated by using a simple random walk MM.

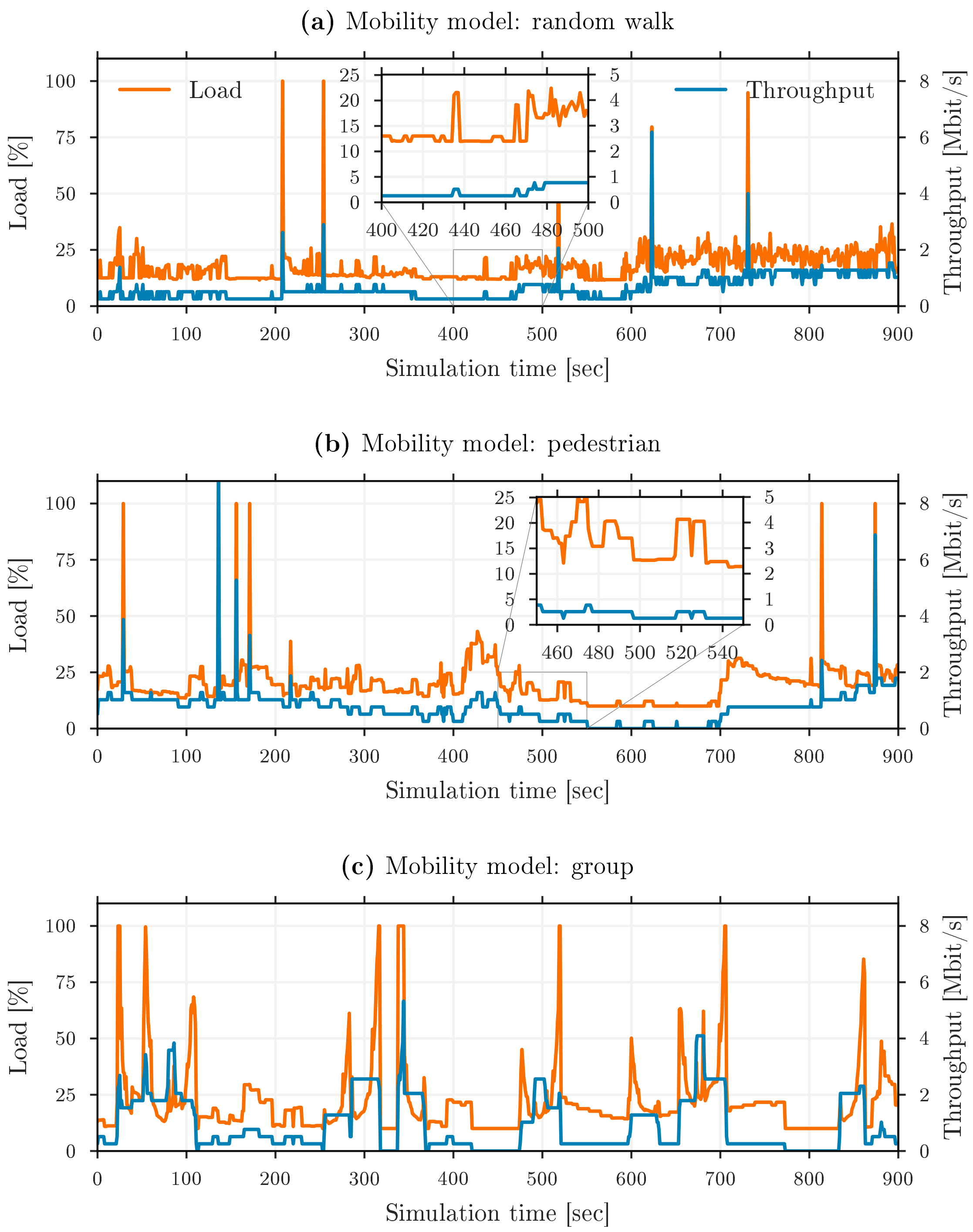


Figure 3.13: Load and throughput for one cell in the scenario

To be more precise, the load and throughput values for one exemplary cell in the scenario, simulated jointly with the just mentioned call model for the random walk, the pedestrian and for the group MM (cf. section 3.1), are shown in Figure 3.13. It can be seen that the random walk users produce a rather steady cell load profile (cf.

Figure 3.13a) since the users are dropped equally all over the scenario area and move in a way that no clear directions are observable. Likewise, the pedestrians also produce a similar cell load profile (cf. Figure 3.13b), comparable to the random walk MM. This is because of slow velocities and steady but aim-oriented movements of the single users. On the other hand, the group mobility users produce several spikes in the load and throughput (Figure 3.13c highlights exemplary cell spikes by a grey area). This is due to the greater number of users that travel *simultaneously* through the scenario. If a train reaches the cell border, the (user) SINR conditions degrade for all the users in that train also resulting in an increase of resource consumptions of the cell.

Such performance behaviour can be crucial and needs to be considered. Particularly in an optimisation scenario, SON functions need to react (quickly) to changing performance conditions. This is another indication that a standard random walk MM (and simplified network topologies) is not sufficient to simulate the behaviour of an advanced and complex mobile radio system with its rapidly changing conditions.

3.3 Concluding Remarks

After considering different Mobility Models (MMs) and evaluating the impact on KPIs in a realistic mobile network scenario, the following concluding remarks can be made:

- The evaluations included three main Handover Performance Indicators (HPIs), the Handover Success Ratio (HOSR), the Handover Failure Ratio (HOFR) as well as the Ping-Pong Handover Ratio (PPHOR). The results show that for each HPI distinct differences between the MMs exist. The variations are often explainable by the aim-oriented movements of the realistic MMs compared to the aimless trajectories of the random walk users. Furthermore, the realistic network scenario can have a profound impact on the HPIs because of its inhomogeneous layout (cf. Figure 3.1) and scattered cell borders (cf. Figure 3.11b). On the contrary, the random walk MM often shows an HP that does not feature special characteristics or outliers towards any direction.

- A weighted combination of three main HO metrics for the two mobility mixes reveal the following: the overall HP for the entire network match each other quite well, meaning that the two different mobility modelling approaches lead to similar results. But, as soon as the performances of individual cells are compared, the differences are striking. Whereas the random walk MM leads to equal results throughout the scenario, the realistic mobility mix produces unique HP profiles on cell-level.

- Beside the actual HO metrics, i.e. the HPIs, realistic MMs can have a profound impact on other KPIs as well. Figure 3.13c gives an example on the cell loads in Figure 3.13c where we compared the traditional random walk MM with the group MM from subsection 3.1.5. Only with the more realistic MM (i.e. the tram mobility from subsection 3.1.5) a unique cell load profile is observable – including a higher variation and spikes at certain times. This is of great importance when deciding to use SON functionalities since SON shall react (quickly) on changing network conditions.
- Finally, when it comes to network management solutions, the simulation of a mobile radio system is only feasible with sophisticated MMs that incorporate realistic movements and behaviours that all lead to a unique network performance. Traditional and straightforward mathematical solutions can hardly be characterised as such. Hence, MMs based on real geographical data are the only answer when evaluating, and testing (self-organising) network management functionality like it is done in this thesis.

Chapter 4

Cell Classification and Network Simulation Scenarios

This chapter presents a method to classify cells based on environmental context attributes. The concept of cell classes is explained in section 4.1 to enable a thorough SON analysis and a sophisticated (self-organising) network management later on. After that, the simulation scenarios used are described in section 4.2. All scenario boundaries are a subset of the so-called "Urban Hannover Scenario" (cf. [Ros+13c] and [Ros+16a]) which is an outcome of the European COoperation in Science and Technology (COST) action "IC 1004" [COS11]. The "Urban Hannover Scenario" is an accumulation of realistically planned mobile networks in the city of Hanover, Germany. It consists of multiple Radio Access Technologies (RATs), several cell layers, and thousands of individual (realistic) user movements (see chapter 3). It was widely used in the EU FP7 SEMAFOUR project [Ros+13a] as well as in several dissertations, e.g. [Jan16]. In a final step, the major modelling assumptions and the default (simulation) parameters used are presented in section 4.3.

4.1 Cell Attributes and Classification

This section describes the characterisation and classification of cells based on context attributes. The concept was developed in the EU FP7 SEMAFOUR project [Göt+15, pp. 35] and is described in [Hah+15a]. With the classification of cells, the MNO gets the possibility to define KPI targets for a group of cells in the network. For example, *all* rural cells at midnight might have a different prioritisation regarding throughput, compared with small cells in a dense urban environment. Otherwise, the definition has to happen individually for each and every cell in the network, which naturally leads to a very time-consuming task. Additionally, cell classes allow a more detailed (KPI) data analysis by not only focusing on the (overall) performance of the entire network but also taking dedicated cell types into consideration.

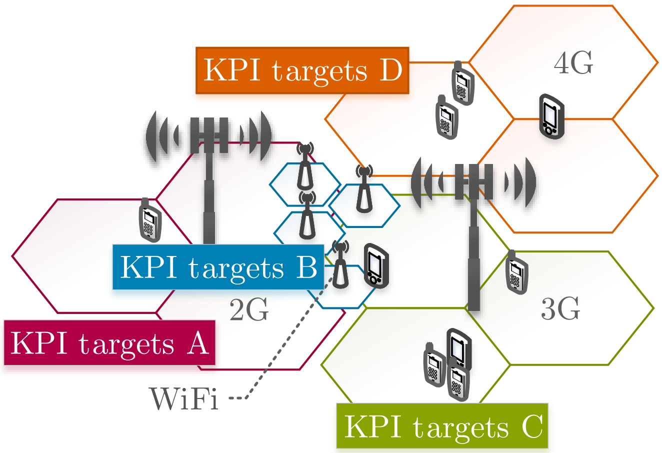


Figure 4.1: Example for different KPI targets in the network with multiple RATs (i.e. 2G, 3G, 4G or WiFi) and different cell layers (e.g. small (WiFi) APs and large (3GPP) cells)

Having outlined the main arguments for cell classes, Figure 4.1 illustrates four class examples with the corresponding KPI targets. Targets A to D are RATs-specific, whereas target B also considers small cells. In this little example, the MNO would already have to define 13 individual targets for every cell in the network. However, with classifying and combining cells instead, four targets need to be defined. This classification of cells is explained in the following.

4.1.1 Cell Attribute Descriptions

In order to allow a classification of cells, an attribute definition needs to be available that describes the context a cell is operating in. For this thesis, five *cell context attributes* are considered in total, namely: the technology, size, location, prevailing mobility type, and the actual data traffic conditions of each cell. Other context attributes (or as a replacement to those mentioned) are possible as well. However, eventually, the MNO has to specify the respective cell context attributes of importance. At first, the herein attributes used are introduced and motivated. The next sections motivate the different attributes used in this thesis.

4.1.1.1 Cell Technology

The RATs an MNO has at hand is an ever increasing source of complexity. GSM, UMTS, and LTE are just three technologies that are present in today's networks.

By including WiFi, and with the 5G on the horizon, the complexity will increase further. To cope with this complexity, SON functionality can be used. However, those functions are often designed to work only for one specific technology (e.g. LB or RO that are designed for LTE, see subsection 2.2.1 and subsection 2.2.2). Other functions try to steer the mobile traffic between different technologies (e.g. LTE/WiFi TS, see subsection 2.2.3). For this thesis, two technologies are considered: *LTE* and *WiFi* (a technical description of both can be found in subsection 2.1.3).

LTE: As of the end of 2015, the rollout of LTE has almost been completed in Germany, meaning that availability in each household has reached at least 90 % in each federal state, see Figure 4.2 [Tec16]. With this, it is safe to assume that an MNO can provide LTE to virtually all of its customers. Moreover, an operator might have specific objectives for a RAT that provides the coverage of its network, e.g. to ensure a satisfying HO behaviour to provide a good QoS. On the other hand, one goal is always to keep CAPEX as little as possible, so a good usage of the available resources, e.g. cell sites, frequency spectrum, etc., is always desired.

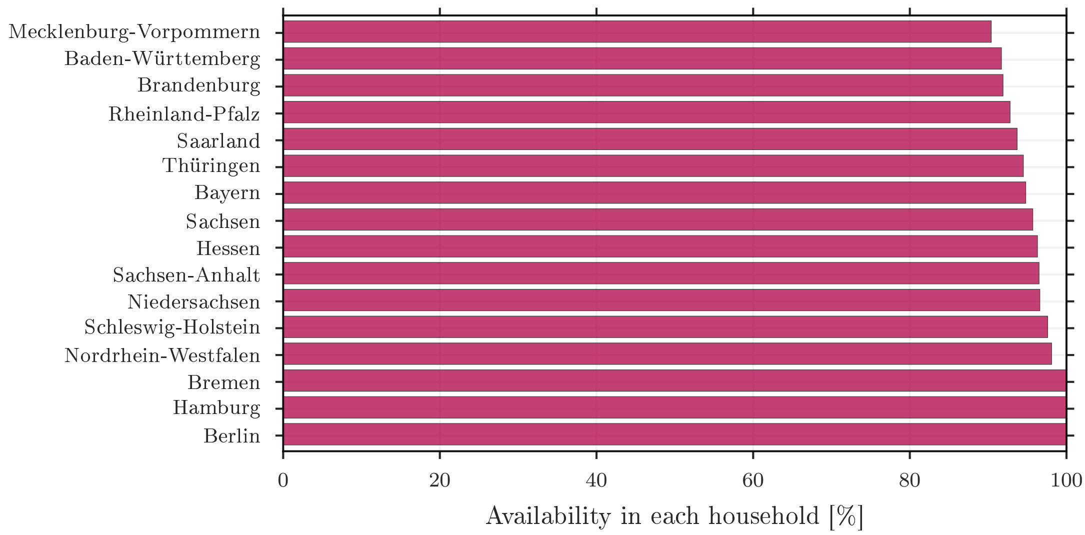


Figure 4.2: Availability of LTE in Germany as of end of 2015 [Tec16]

WiFi: With WiFi, on the other hand, the MNO has a good alternative available to provide capacity by offloading data traffic from the LTE network [3GP17b]. In Figure 4.3, the online video streaming behaviour in Germany is shown. It is noticeable that roughly two-thirds of those polled stated that they watch such videos via WiFi and only a small fraction is using the cellular network [TNS15]. Now, of course, this behaviour might change in the following years, but such user habits should be taken into consideration if an MNO also (partially) operates a WiFi network. This WiFi usage is leading to objectives that focus on improving the QoE, e.g. greater cell throughput. Apart from that, WiFi APs are much simpler to deploy and do not need a time-consuming planning phase, compared to LTE.

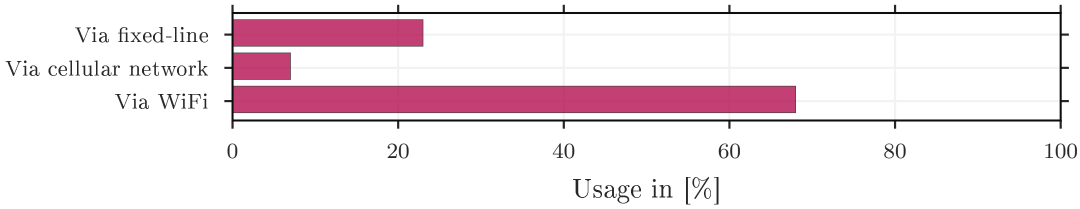
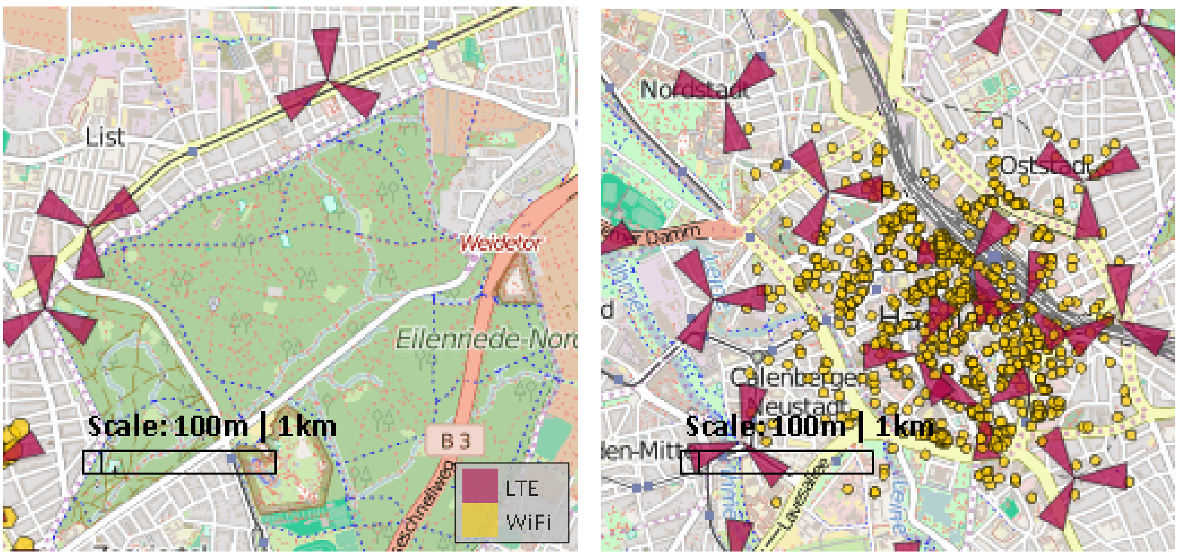


Figure 4.3: Online video streaming usage in Germany as of end of 2015 [TNS15]

4.1.1.2 Cell Location

The location gives a first indication of the purpose of the cell. A site in a rural area might be used to provide sufficient *coverage*, whereas a cell-site located in the city centre has to add (more) *capacity* mainly. Therefore, possible cell locations are rural, suburban, urban, indoor or deep-indoor. Only two location types are considered here: *rural* and *urban*. The reason for that is to keep the complexity to a certain level by having to consider a reasonable amount of total cell attributes only. Moreover, it is easily possible to simulate these two location types with the given "Urban Hannover Scenario". Figure 4.4 shows two examples for both cell locations.



(a) Rural **(b)** Urban

Figure 4.4: Parts of the "Urban Hannover Scenario" for different cell locations

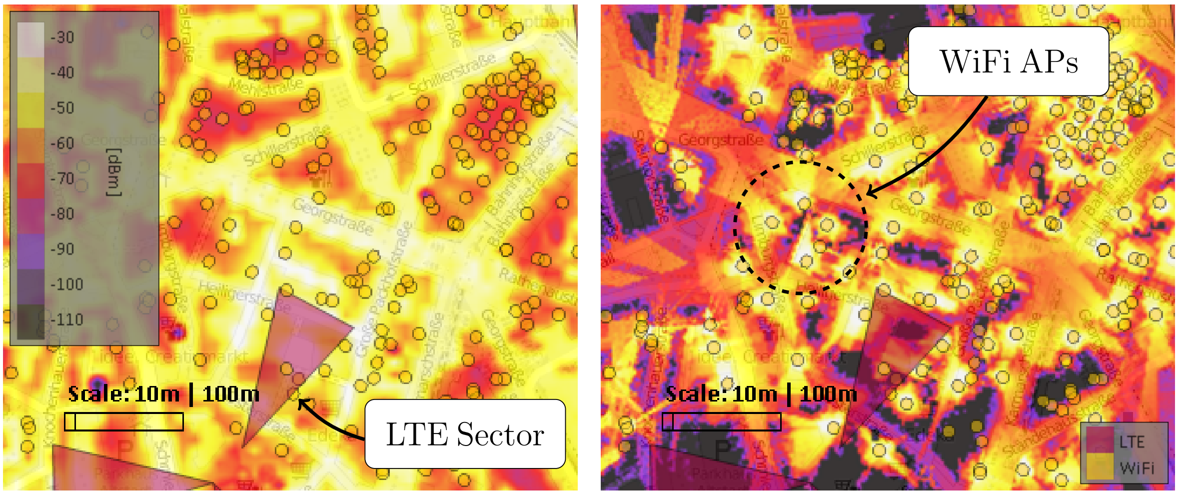
Rural: As mentioned, rural cells are mainly supposed to provide coverage, but also the total data traffic demand is simply lower. The operator takes this fact into consideration during the planning of the mobile system. Hence, a rural network is rather sparse regarding cell locations. This can also be observed in Figure 4.4a. The benefit of this is that fewer cells (that are providing the mobile service) are covering larger parts of the network. On the other hand, the HO operating point has to be carefully chosen to guarantee a certain level of QoS in order to prevent a critical Handover Performance (HP) (see chapter 3), because the mobility traits can vary significantly – ranging from pedestrians walking in parks to high-speed users on motorways. Therefore, a potential KPI target for cells in a rural location might be able to improve the HP.

Urban: An urban location is often characterised by a high user population density. Consequently, also a higher total mobile data traffic demand can be expected. This request has to be reflected in the planning phase of a mobile radio network. By *decreasing* the inter-site distance of the cells the capacity in the system can be *increased*. A high cell-site density can be seen in Figure 4.4b. A potential KPI target formulation for cells in an urban location can be to improve the QoE, for instance by maximising the user throughput performance.

4.1.1.3 Cell Size

Besides the location, the size gives another strong indication of the purpose of the cell. Large cells, also known as *macro* cells, transmit with high power and are typically located above the rooftops. The antennas in the realistically planned LTE layer, operating at 1800 MHz, transmit with a power of 46 dBm, whereas the *femto* and *pico* cells, which are hereafter referred to as *small cells*, transmit with 23 dBm. Figure 4.5 presents the differences in the path loss predictions. Here, one LTE site (indicated by red triangles) and many WiFi APs (yellow dots) are shown. The differences are clearly visible. The LTE site/layer is able to provide enough coverage for a larger part of the area (see Figure 4.5a). The WiFi APs/layer provide coverage only in the vicinity of the cells, e.g. the home/room where the AP is placed or the street canyon where the building is located (see Figure 4.5b).

Large: Since larger cells are more likely to provide coverage, the KPI objectives might focus on the QoS. This is translatable into providing a good Handover Success Ratio (HOSR). Furthermore, it is more likely that a greater amount of users connect to one particular (large) cell. With this comes the need to provide a proper load balancing to prevent cells from going into an overload situation.



(a) Large (b) Small

Figure 4.5: Path loss predictions for different cell sizes

Small: Small cell areas usually lead to a bad HP due to a sudden RSS variation. On the other hand, good throughput values can be achievable because only a few users compete with others over the available resources (e.g. bandwidth). As small cells are mainly supposed to provide capacity, one objective might be to save energy at night. At night-time, the data traffic demands are simply lower, compared to the busy hour, so that several (small) cells can be switched off.

4.1.1.4 Mobility Type

The ability to move seamlessly through a system without any connection problems is one of the key features of a mobile radio network. However, as chapter 3 has shown, the nature and degree of mobility can have a severe impact on the HO metrics and, thus, the HPIs. Therefore, the user movement has to be treated accordingly by adjusting the (HO) parameter of the system. Two types of user movements are further considered here: *normal* and *high-speed* mobility.

High-Speed: Users that travel at high-velocity feature a "high-speed" mobility profile: for example, vehicles on a motorway or speedway. Since rural scenarios often also feature motorways, the cell density is rather sparse. These fewer cell locations might also lead to an increased RLF performance due to misadjustment of the HO operating point and a quick penetration into a neighbouring cell due to the high velocity. Moreover, high-speed users are usually not keen on using traffic types that require a high data rate (e.g. high definition video streaming), so the focus can be to guarantee the best HP.

Normal: Everything else apart from "high-speed" users is considered as a "normal" mobility type. This type covers pedestrians, vehicle users in the city, local public transportation (such as a tram or bus) and indoor users. As subsection 3.2.2 showed, pedestrians with a low-velocity feature a small HOFR. So an MNO might improve other KPIs, apart from the HP.

4.1.1.5 Data Traffic Type

Changes in the data traffic demands is another difficulty that the mobile radio system has to deal with. A high traffic demand usually means a high load of the system. In addition, these requests also lead to degraded SINR conditions, due to a higher interference level in the network. In consequence, a degradation of the HOF and RLF performance is to be expected. However, the MNO wants to guarantee a certain level of QoE – especially in these high data traffic demand situations. On the other hand, lower data requests, e.g. at night-times, might be suitable to shut down entire sites to save energy. There are many methods to measure the actual traffic situation, for example, the cell throughput, the number of connected users or simply the time of day. Most of them lack the ability to clearly determine if the data traffic is "normal" or "busy". Therefore, for this thesis, it is based on a Simple Moving Average (SMA) of the cell load. The SMA is calculated based on Equation 4.1, where w is the window size, $\rho(t)$ the cell load value (cf. subsection 2.3.1) at time t, and i is a previous time step [PM06, pp. 837]. The window size is set at five minutes. Two types are used: a *normal* and a *busy hour* traffic type.

$$\rho^{(w)}_{SMA}(t) = \frac{1}{w}\sum_{i=0}^{w-1}\rho(t-i) \tag{4.1}$$

Normal Hour: A normal hour is given when the average cell load is below 50 %. This threshold, as well as the window size w, can be defined by the MNO. Since the cells are usually not in an overload condition (and LB actions are not required), the MNO can focus on other KPIs, such as the HOSR.

Busy Hour: If the average cell load is above the 50 % threshold the data traffic condition is considered to be busy. Here, an MNO might still want to provide an excellent cell throughput and, hence, try everything to assure it (for example by LB measures). Note that a common definition for the busy hour is often represented by the maximum traffic that a network/cell must support in one hour [Fre05, p. 57] – so it is *one* hour and cannot dynamically change over the day.

4.1.2 Cell Attribute Determination

Now, with the given cell attributes, coming as input from the MNO, actual classes of cells are derivable. For that, it is necessary to assign the current attributes to the respective cells in a correct manner. In other words: When is a cell considered to be in a *rural* or *urban* environment? Or: When is it most likely that the prevailing mobility profile is considered to be *high-speed*? To answer these questions, methods to determine the cell location and the mobility type, based on geographical data, are described below.

4.1.2.1 Determination of the Location Type

Geographical data have to be available to determine the cell location. An example for that shows Figure 4.6. The different colours represent so-called "land-use classes". Such information is most likely available for the MNO anyway since it is also needed for the prediction and planning of the network. Sources for this kind of data might be official administrative bodies, e.g. the land registry office, or open data initiatives, such as the OSM project [Ope], [HW08].

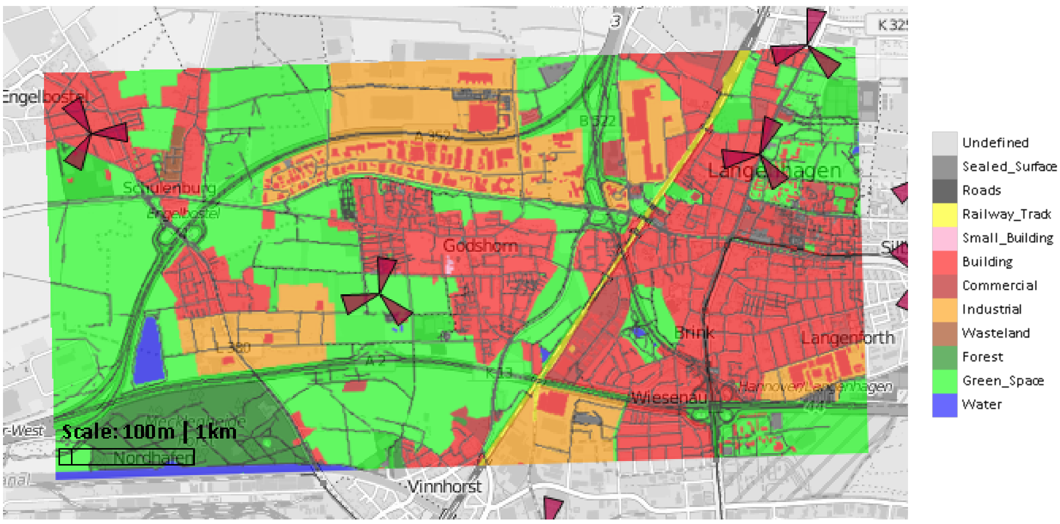


Figure 4.6: Exemplary clutter data

The question now is, what kind of clutter information (which is also another term for land-use classes) lies within the boundaries of the cell areas. To answer this, a definition for "cell area" has to be given first. One possibility is to use the so-called Best Server Map (BSM). A BSM shows the respective IDs of the cells with the highest RSS values. With that, a hard-decision is made when a "pixel" (i.e. geographical reference area) belongs to a dedicated cell or not. An example for a section of the "Urban Hannover Scenario" is given for a BSM in Figure 4.7.

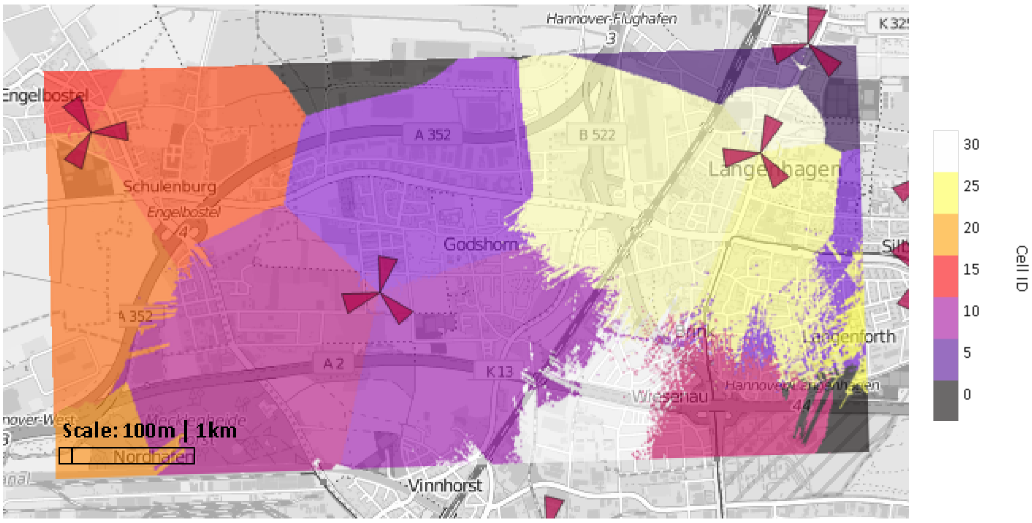


Figure 4.7: Exemplary BSM

Another possibility to define cell areas is to use Cell Assignment Probability (CAP) values [Hec12, pp. 19]. CAP maps make use of fading effects, which result in time-varying BSMs. By that, the cell borders "soften" and a clear decision when connecting to the best server turns into a *probability*. This concept is used in the following to determine the cell boundaries. A CAP threshold specifies when a cell ID belongs to a cell area or not.

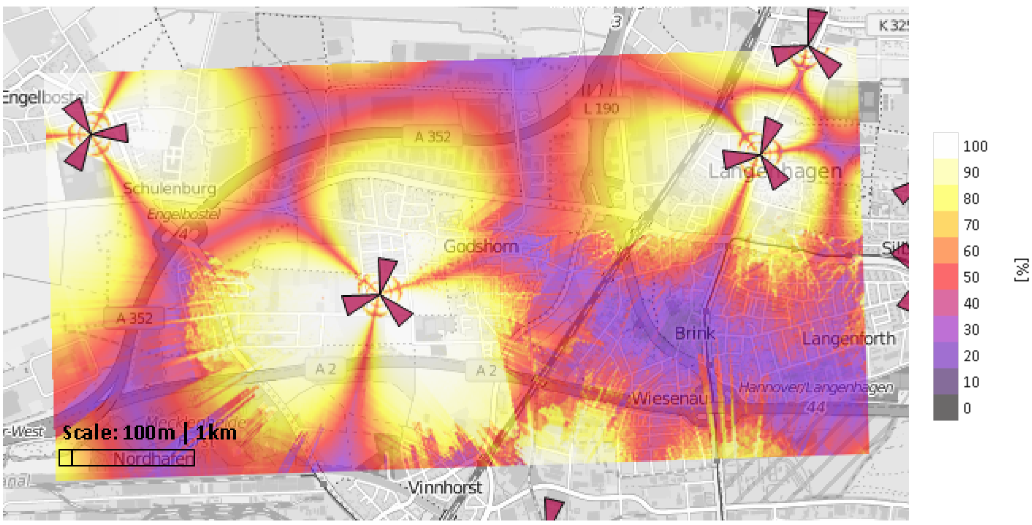
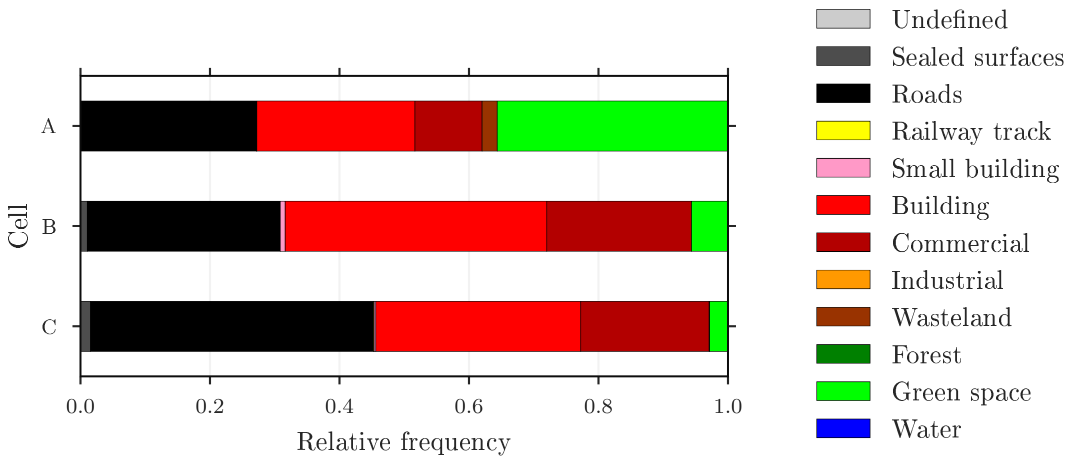
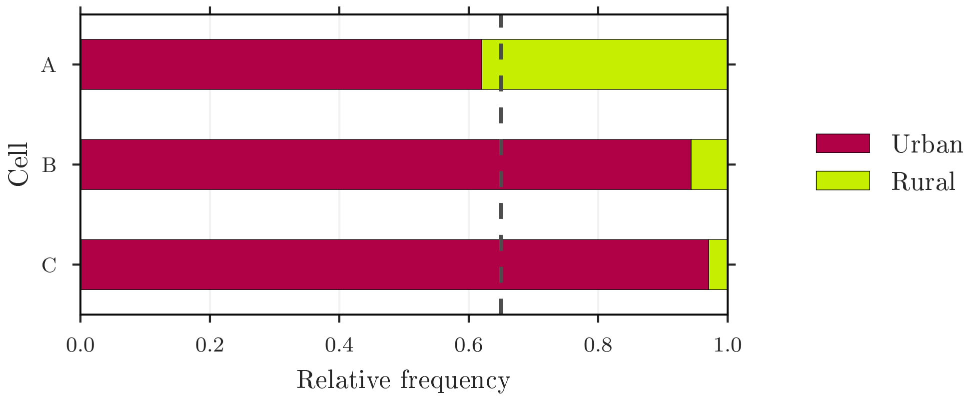


Figure 4.8: Exemplary CAP map

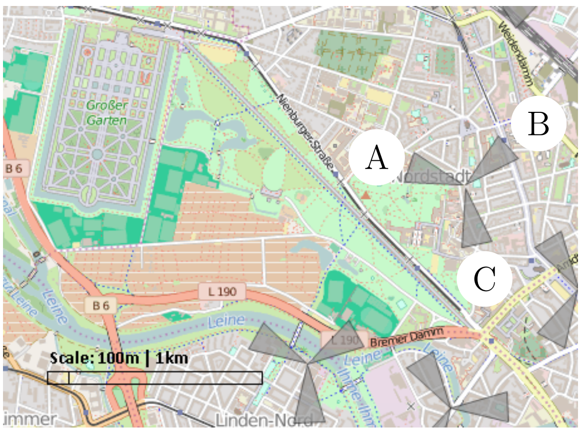
With the given cell areas the clutter information can be mapped to the respective cells. Figure 4.9a provides an example for that. Here, the approach leads to a relative distribution of the available land-use classes for a typical site consisting of three cells in the scenario (cell "A", "B" and "C" as shown in Figure 4.9). Now, by combining land-use classes that stand for *rural*, such as "Wasteland", "Forest" and "Green space", and



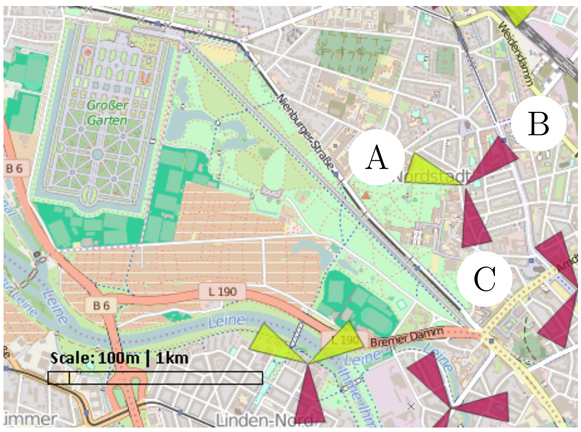
(a) Distribution of the clutter information for Cell A, B and C



(b) Processed clutter information that determines the cell location



(c) Before determination



(d) After determination

Figure 4.9: Exemplary cell attribute determination (here: the location of a cell)

land-use classes that stand for *urban* (all remaining ones) a relative distribution for the two location types can be made (cf. Figure 4.9b). The MNO has to define when a cell is considered to be *rural* or *urban*. This determination can be done by (again) setting a threshold. The value here is set at 0.65 which satisfies a reasonable fitting based on extensive simulations and check-ups with the available scenario data. The threshold is also indicated by a black dashed line in Figure 4.9b. This specific example is also visualised in Figure 4.9c and Figure 4.9d by showing the actual geographical location of the cell-site. The left side presents the cells before the attribute determination. On the right, the cells are coloured according to the respective location type.

Other possibilities to determine the location of a cell is simply to consider the raw geographical information. If the cell is located within the bounding area of a city with a given population size, it is determinant to be an urban cell. If the population is below a defined threshold, the cell is considered to be rural.

4.1.2.2 Determination of the Mobility Type

The mobility type is mainly bound by the road information. For example, if a highway cuts across a cell area, the cell can be considered to feature a *high-speed* mobility profile. Again, the information about cell areas and road data are needed. The road data can be accessed by, e.g., OSM data. Exemplary route information for the section of the "Urban Hannover Scenario" is shown in Figure 4.10. Red indicates highways; yellow represents railway tracks and purple stands for all remaining road types.

Figure 4.10: Exemplary road data

Another way to automatically determine the mobility profile is to retrieve the velocity of the UEs. For that, the 3GPP standardised a corresponding procedure [3GP13]. If the dominant user speed is above a pre-defined threshold, the mobility type is *high-speed*. By this, the context attribute becomes dynamic. However, the amount of data that needs to be processed increases even further. Furthermore, OSM data sometimes also provide speed limits of the streets, which can be used as well.

4.1.2.3 Determination of the Remaining Context Attributes

The determination of the remaining three context attributes, i.e. technology, cell size, and traffic type, is not based on geographical data. The technology of a cell is given and fixed – it is either LTE or WiFi. The cell size (here) originates from the transmit power. Of course, other indicators concerning the size are possible, but as for this thesis, antennas that are transmitting at 46 dBm are considered to be large cells. A transmit power of 23 dBm or lower leads to a small cell size. Hence, all LTE cells are large, and all WiFi cells are small for the remainder of this thesis. The last parameter, i.e. the traffic type, is the only attribute that can change dynamically over time. It is determined based on the cell load values, with an SMA as described in subsection 4.1.1.

4.1.3 Cell Classification

With the available and determined context attributes for all cells in the network, it is finally possible to define cell classes. The actual definition of each class has to be done by the MNO – preferably in a machine-readable language, e.g. in a form as given in Equation 4.2. The MNO has to decide what combinations of context attributes and what kind of KPI target value differentiations are of importance based on individual preferences. This reduction of context attributes is also the greatest advantages of cell classes compared to a vast accumulation of context attributes. The MNO only has to define objectives for the given set of cell classes and not for each and every context combination in the network.

$$Class_N = \{Attribute_1, Attribute_2, \ldots, Attribute_M\} \tag{4.2}$$

The variations of combinations can quickly explode. For instance, the five attributes used herein are: the two cell technologies, two sizes, two locations, two mobility types and two data traffic types. This already leads to $N_{element}^{N_{attribute}} = 2^5 = 32$ combinations. Only eight defined cell classes are needed instead, which are of real importance of this (fictional) MNO. Now, this is a still relatively small amount of possible attribute combinations. In a real network with multiple RATs (e.g. GSM, UMTS and LTE), different cell sizes (from macro to femto) and more diverse cell locations (e.g. rural to deep-urban) the needed attribute combinations can quickly reach a couple of thousands as exemplarily shown in Figure 4.11. This is the moment when cell classes can unfold its real potential to minimise the number of context combinations worth considering.

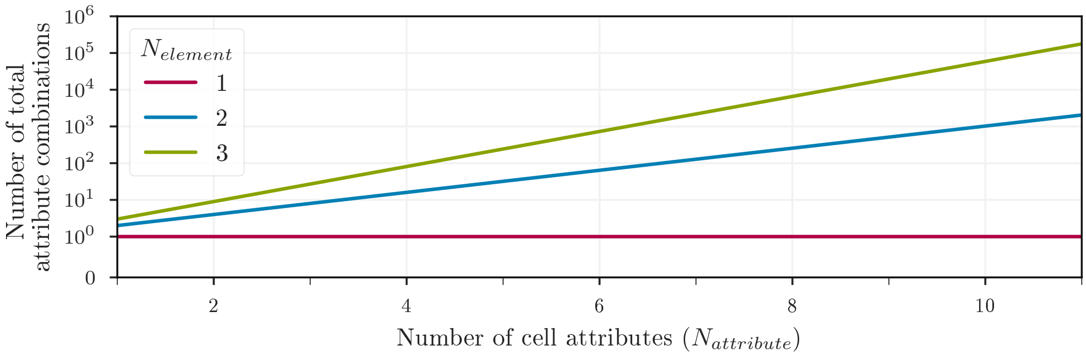


Figure 4.11: Total number of attribute combinations for different amounts of attributes and elements of each attribute

Finally, Table 4.1 lists all the formulated classes for this thesis. In total eight classes are used in chapter 5 and chapter 6, that cover different combinations of context attributes. The classification becomes time-variant due to the traffic attribute, which is checked every 15 minutes in the simulations. If no attribute combination fits a class definition, a default class is chosen ($Class_{-1}$, see last row of Table 4.1). Other class definitions are possible, but the ones here can easily be simulated with the given scenario.

Table 4.1: Defined cell classes for the scope of the thesis

Class	**Context Attribute**					
ID	*Technology*	*Size*	*Location*	*Mobility*	*Traffic*	*Colour*
1	WiFi	Small	Urban	Normal	Normal	
2	WiFi	Small	Urban	Normal	Busy	
3	LTE	Large	Urban	Normal	Normal	
4	LTE	Large	Urban	Normal	Busy	
5	LTE	Large	Rural	Normal	Normal	
6	LTE	Large	Rural	Normal	Busy	
7	LTE	Large	Rural	High-speed	Normal	
8	LTE	Large	Rural	High-speed	Busy	
-1	N/A	N/A	N/A	N/A	N/A	

Figure 4.12 shows an example for the defined cell classes in the "Urban Hannover Scenario". Several observations can be made:

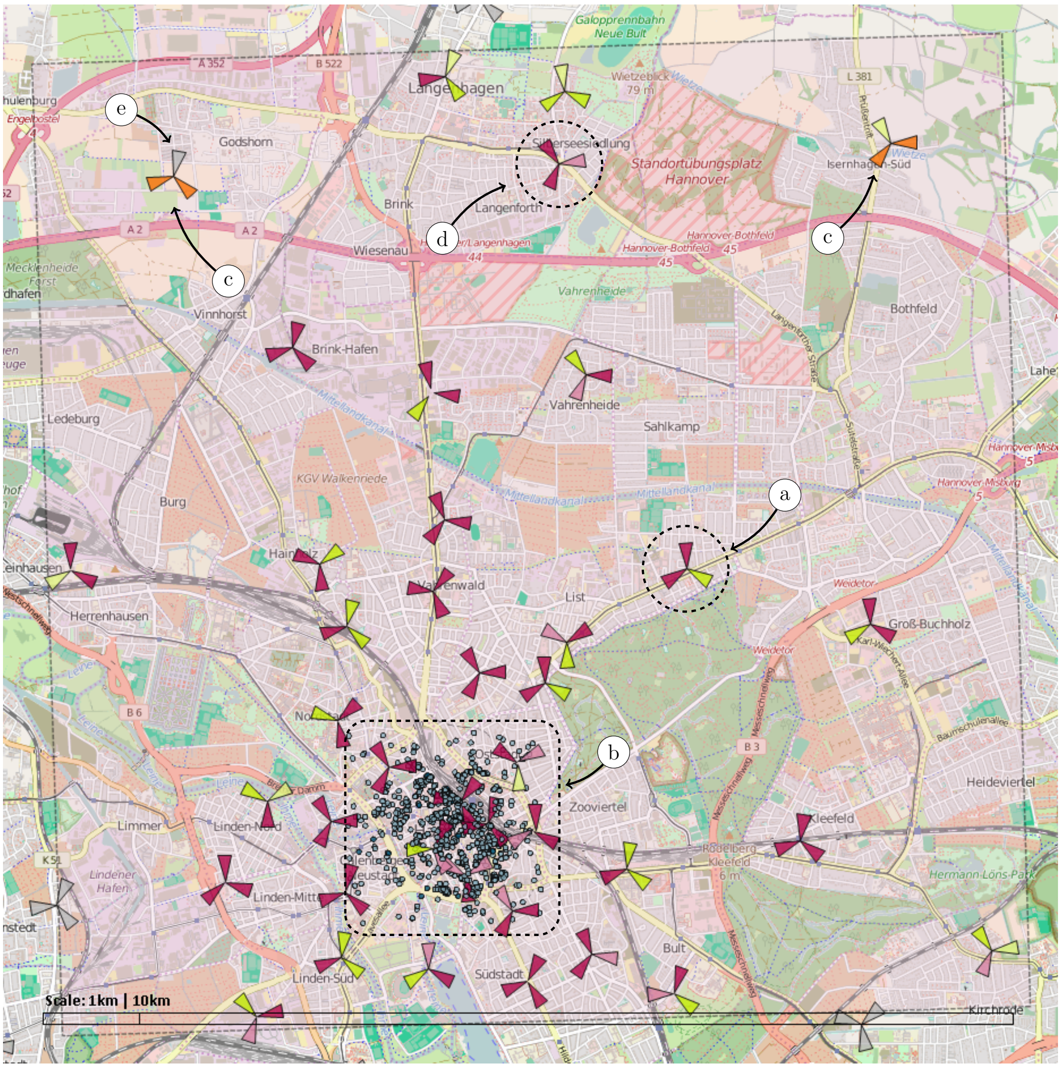


Figure 4.12: Exemplary cell classification covering an area of 100 km^2 in the "Urban Hannover Scenario"

a) *Rural* and *urban* cells can be differentiated, shown in green and red triangles respectively (note that the colours correspond with the last column in Table 4.1).
b) The WiFi APs in the city centre are all labelled as *small* cells (blue dots).
c) Cells that mainly cover motorways are tagged as *high-speed* (orange triangles), see upper sites in Figure 4.12.
d) Different data traffic types can be observed: Cells operating in the *normal hour* are shown in light, cells in the *busy hour* are shown in bright colours.
e) One cell does not match any class definition. Hence, the *default* class is chosen (grey triangle), see top left cell-site in Figure 4.12.

4.2 Simulation Methodology and Network Evaluation Scenarios

This section describes the simulation methodology, which mainly defines how results are obtained for the course of this thesis. Furthermore, the simulation scenarios used, i.e. *"A"* (also referred to as scenario with an Urban location and Normal mobility mix (UN)), *"B"* (a simulation area with a Rural location and Normal mobility mix (RN)), *"C"* (a scenario with a Rural location and High-speed mobility mix (RH)), and *"D"* (also referred to as $10\,\mathrm{km} \times 10\,\mathrm{km}$ – Reference and Evaluation Scenario (10X10)) are characterised, described and analysed, respectively.

4.2.1 Methodology

As explained in chapter 2, the results for this thesis are conducted by using microscopic simulations. On the one hand, this includes individual (realistic and a varying amount of) user movements (see also Figure 4.21). Mobility in a mobile radio network requires a handover decision algorithm to guarantee a seamless transition of voice calls or data sessions. For that, the HO algorithm herein used is based on the implementation of [Jan16, pp. 25] and is in accordance with specifications of 3GPP [3GP13]. On the other hand, data sessions for each user are needed to generate mobile data traffic in the system. This data traffic generation is done by defining a call session model with different service types as characterised in Table 4.2. Since modern UE devices are capable of handling several sessions at the same time, multiple services can run in parallel as well [Neu16, pp. 15]. The five data service types are the following:

Voice Call: A (classical) voice call has a mean duration of 60 sec, derived from an exponential distribution [Kri16, pp. 203]. The inter-arrival time is modelled in a traditional way by using a Poisson process [Kri16, pp. 89] with a rate of 120 sec [ETS97, pp. 34]. The requested data rate is set at 13.3 kbit/s [Mol11, pp. 595]. This service type has a finite buffer size, which means that the application drops packets if the buffer is full due to an unserved traffic demand. Note that in the following, the term *"unserved"* here means that if a user did not get the requested data rate, e.g. 13.3 kbit/s, the remaining amount of data is added to the next data request (see also subsection 2.3.1). If the application cannot empty the buffer within 1 sec, the call gets terminated. Voice calls are only possible if the user is connected to LTE since WiFi systems currently do not support the traditional voice call setup. WiFi "calls" (e.g. using WhatsApp) are seen as CBR traffic. Table B.1 in the appendix also summarises this traffic type.

Table 4.2: Parameters of the data traffic session model

Parameter		**Service type**				
Name	*Unit*	*Voice*	*Video*	*CBR*	*FTP*	*Web*
Technology	N/A	LTE	LTE WiFi	LTE WiFi	LTE WiFi	LTE WiFi
Buffer type	N/A	Queuing-lost	Queuing	Lost	Queuing	Queuing
Duration (mean)	[sec]	60	300	∞	–	–
Inter-arrival time	[sec]	120	300	–	300	30
Data request	[kbit/s]	13.3	NGMN$^\blacklozenge$	64.0	Best-effort	Best-effort
File size (total)	[kbit]	–	–	–	NGMN$^\bigstar$	NGMN$^\blacktriangle$

$^\blacklozenge$[Irm+08, p. 22], $^\bigstar$[Irm+08, p. 20], $^\blacktriangle$[Irm+08, p. 21]

Video Streaming: These sessions are modelled on parameters provided by the NGMN consortium (see [Irm+08, p. 22] or Table B.2 for further explanations). The mean duration (using an exponential distribution) and the inter-arrival time (generated by a Poisson point process) are both set at 300 sec. If the system cannot serve the required data traffic demand sufficiently, the remaining amount gets collected in an (infinite) buffer. It tries to reduce the buffer in the following time steps. Hence, no data gets lost.

Constant Bit Rate: To provide a continuous data request in the network, a Constant Bit Rate (CBR) traffic model with a data rate of 64 kbit/s applies to all users in the system. In consequence, the duration of this service is set to infinity. All unserved data gets lost because this traffic type does not allocate any buffer capacity. With this, the system can be brought to a certain level of resource utilisation to provide a minimum degree of load in the cellular network.

FTP Download: To account for large data files, a File Transfer Protocol (FTP) service type based on the definitions of NGMN is used (cf. [Irm+08, p. 20] or Table B.3). A file transfer starts after the previous download has finished and the inter-arrival time (using an exponential distribution with a rate of 300 sec) has expired. The requested data rates cannot be specified because it is based on a best-effort approach (hence the "–" in the *FTP* column of Table 4.2). In other words, the user gets the highest data rate the system can offer. No unserved traffic demand gets lost. Such best-effort service usually leads to a fully loaded cell due to the infinite data demand.

Web-Browsing: Similar to the previous service type, web-browsing is modelled again based on NGMN recommendations. A web page here contains one *main* object and several *embedded* objects. The size of the main and the embedded objects are based on a truncated Log-Normal distribution [Kri16, pp. 305]. The actual number of embedded objects is derived from a truncated Pareto distribution [Kri16, pp. 315]. The UE tries to download the whole web page with the highest available data rate. Also, no unserved traffic gets discarded, and the inter-arrival is modelled using an exponential distribution with a rate of 30 sec. For a detailed listing of all parameters of the different distributions the reader is referred to [Irm+08, p. 21] or Table B.4 in the appendix.

4.2.2 Scenario A: *Urban Location with a Normal Mobility Profile*

The first scenario definition that is used for the remaining chapters of this thesis covers the inner city of the "Urban Hannover Scenario". Figure 4.13 shows the bounding box of the area. Table C.1 in the appendix summarises the technical parameters. The region is supposed to capture key characteristics of a (deep) urban scenario. Such attributes include a significant number of small cells, short inter-site distances of the present macro cells and a higher user population density. Therefore, this scenario features LTE macro cells on the one hand, and over 800 WiFi small cells on the other hand. Compared to the following situations, which are presented in subsection 4.2.3 to subsection 4.2.5, the average user quantity per scenario area is also larger. The four KPIs (defined and described in detail in section 2.3) for this scenario are presented in Figure 4.14. The KPIs are collected using a simulation of three hours. A system without any active SON functionality is considered, which is further used as a baseline to evaluate the impact of SON (cf. chapter 5) on network performance. The plots also feature two colours: one that denotes a normal (*blue*) and another one a busy hour traffic condition (*orange*). The samples of the KPIs are labelled by the traffic condition with the help of the SMA given in Equation 4.1.

The top row of Figure 4.14 shows the Kernel Density Estimations (KDEs) for each KPI, divided into the two traffic conditions. A KDE is a way to estimate the unknown probability distribution of a given set of sampling points. By using Gaussian kernels that are placed over the sampling points (any non-negative function that integrates to one is usable), the estimated distribution is given by the superposition of all kernels. [Sco92] The first subplot (a), i.e. the cell load values, shows the two different traffic conditions. Please note that the values below 50 % are considered to be a "normal hour" and above a "busy hour". Furthermore, as an SMA is used to determine the traffic type, cells with a small(er) load might be labelled as "busy" and vice versa. Hence the visible separation of the two curves at *around* 50 %. The next subplot (b) shows the KDE of the cell throughput. The density functions cover a greater range of values for cells labelled as "busy", which comes as expected because the traffic request is simply higher. The third subplot (c) shows the probability densities regarding the unsatisfied users. One consistent trend that is observable is that the higher the cell load gets, the more users become dissatisfied. Finally, subplot (d) is showing the HOSR for all cells in the scenario. Both traffic conditions feature a high HOSR. This HP is due to the small inter-site distances of the LTE cells. However, a small bump for low HOSR values is noticeable for the "normal hour", due to the bad HP of the WiFi APs in general. This also indicates that the WiFi APs are often less loaded compared to the LTE cells, because WiFi APs use a greater bandwidth (20 MHz compared to 10 MHz used by the LTE macro cells) and usually have only a handful of connected users due to the small cell sizes. The subplots in the second-row present selected pairwise relationships between the four KPIs. The link between cell *throughput* and *load* (see subplot (e)) indicates two characteristics. First, the higher the cell load, the higher the corresponding throughput value. This increase is not an unusual behaviour since a high load means a high traffic demand by the users and thus potential high throughput values. The second observation that is striking is the fact that two shapes of throughput/load directions exist: one with a steep and one with a low rise. This behaviour is due to the presence of two cell layers. The WiFi layer and its corresponding SINR-throughput-mapping (cf. Figure 2.14 in section 2.3) offer more capacity compared to the LTE cells at the edge of the scenario. The relationship between cell *load* and the fraction of *unsatisfied users* (subplot (f)) is similar to the previous one – if the cell load is higher, it is more likely for users in the cell to be unsatisfied. The third relationship shows the coupling between *throughput* and *dissatisfied users*, which follow a similar progression as the previous subplots have shown. The last relationship pair, i.e. *HOSR* and cell *throughput* in subplot (h), however, seem to feature an unusual behaviour. Naturally, if the load is high in a system, the HOSR performance should be worse due to greater interference in the system, because the degraded user SINR values are causing more RLF and HOF events. Yet, some cells with a small throughput and, thus, low load feature a bad HP. The main reason for this behaviour is, again, the presence of different cell sizes. Small cells have smaller cell sizes compared to macro cells, as illustrated in Figure 4.5. Due to this fact, users tend to move out of the cell area faster, which is also a cause for higher RLF- and HOF-rates in the system, and thus a bad HOSR performance.

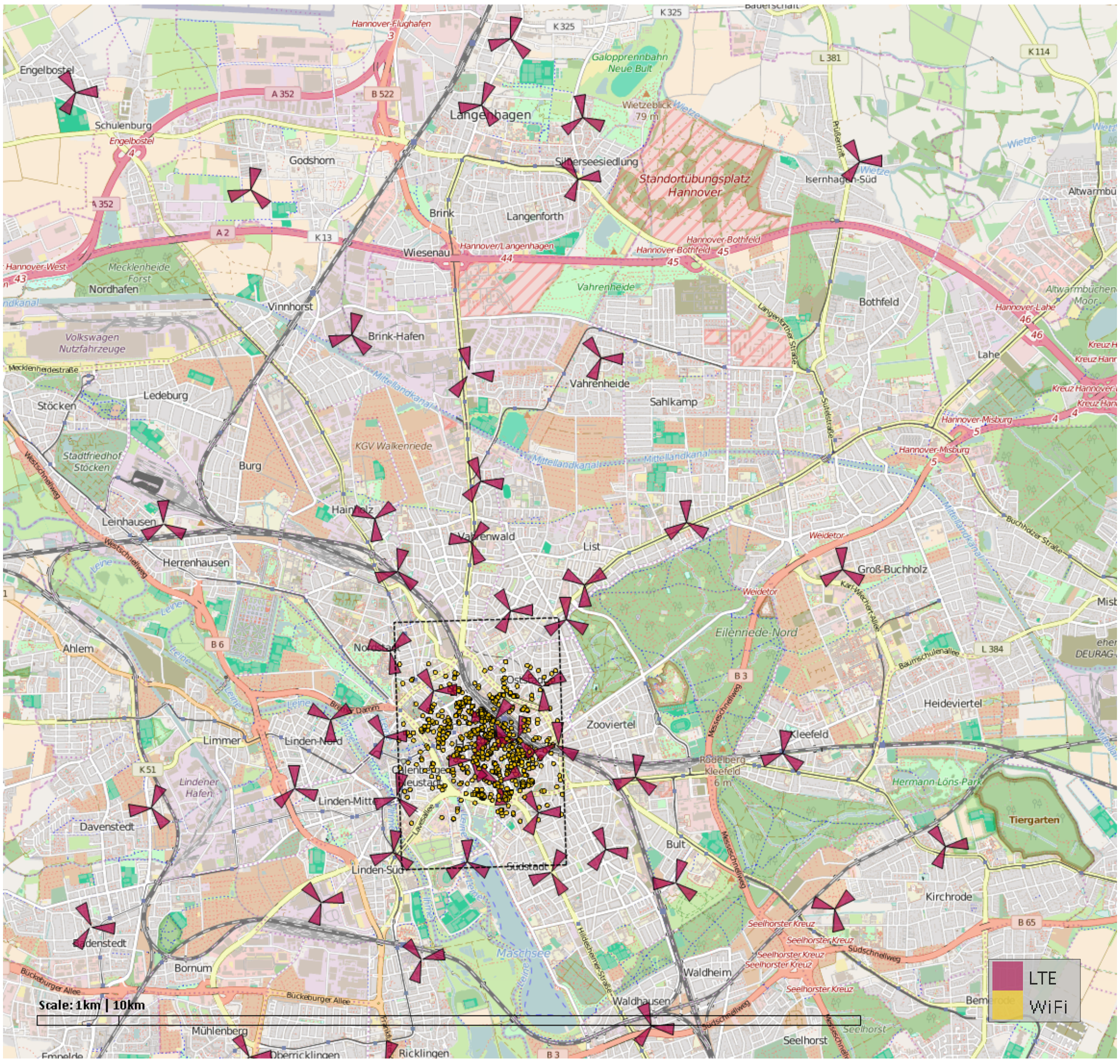


Figure 4.13: Scenario A: *Urban location, Normal mobility profile (UN)*

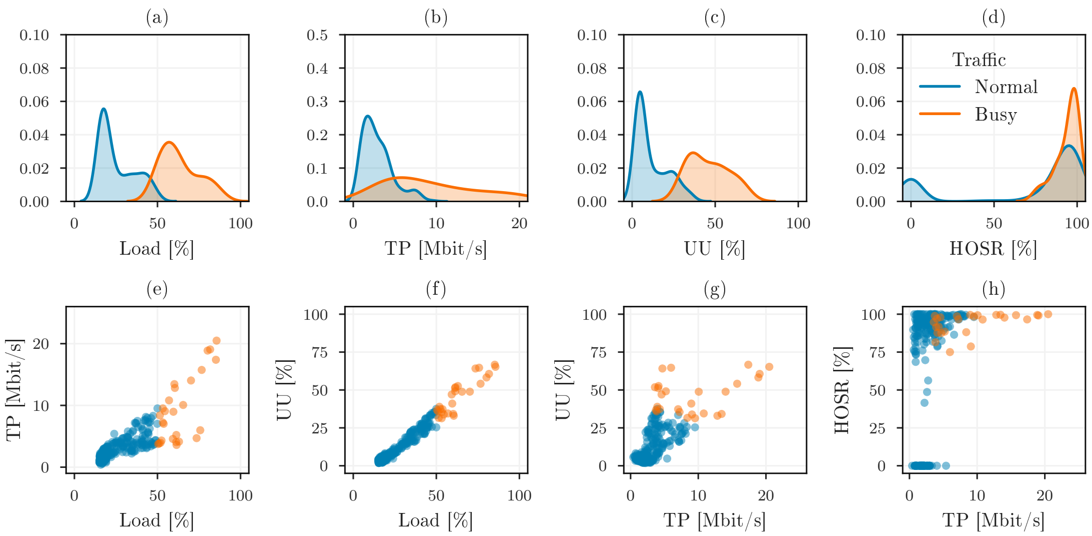


Figure 4.14: KPIs for scenario A, divided into traffic conditions

In short, one can say that the KPI characteristics represent a scenario in a typical urban environment with its multiple cell layers and RATs. Additionally, the well-distributed data traffic accounts for a reasonable amount of cells operating at a normal and the other part at a busy hour (cf. subplot (a)). Moreover, the system is working at capacity, indicated by the presence of the fraction of unsatisfied users, so that SON is indeed needed to improve the network performance. The HO statistics also speak for two kinds of cells. Small(er) cells with a rather bad HP and LTE cells featuring a better one (cf. subplot (h)).

4.2.3 Scenario B: *Rural Location with a Normal Mobility Profile*

The second scenario is supposed to represent a typical rural environment. Hence no small cells are present. Also the inter-site distance of the LTE macro cells is much greater compared to "Scenario A" (cf. subsection 4.2.2). As Figure 4.15 shows, the area features a large amount of "green space" meaning to mimic parks where pedestrians can walk through (see for example Figure 3.4b in subsection 3.1.3). All scenario parameters are summarised in Table C.2. The KDEs and pairwise relationships for the four KPIs are shown in Figure 4.16. The probability density functions for the cell load is again divided into the different traffic conditions. The same applies for the remaining KPIs, the cell throughput, the fraction of unsatisfied users and HOSR. The relationship between cell throughput and load, as well as the fraction of unsatisfied users and the cell load, shows that the higher the cell load, the greater the corresponding KPI. This behaviour is again an expected result (comparable also with the one from subsection 4.2.2). However, one noteworthy observation can still be made: The HOSR and cell throughput (subplot (h), lower right part in Figure 4.16) does not show a clear relationship, i.e. also a low cell throughput/load exhibit a bad HOSR performance. This relationship can be further analysed with the KDE plot of the HOSR (subplot (d), upper right part). Here it can be seen that a normal traffic condition leads to a higher probability of a good HOSR performance, i.e. a shift towards 100 % HOSR. Whereas a degraded HO behaviour occurs for highly loaded cells, making it a reasonable results.

All in all, this scenario features a likely HO behaviour with better performance values if the cells are less loaded (subplot (d)). Adding to this, the cell load and throughput values are not as high as in a (deep) urban scenario, reflecting a fewer data traffic demand as one could expect in a rural environment (subplot (a) and (b)).

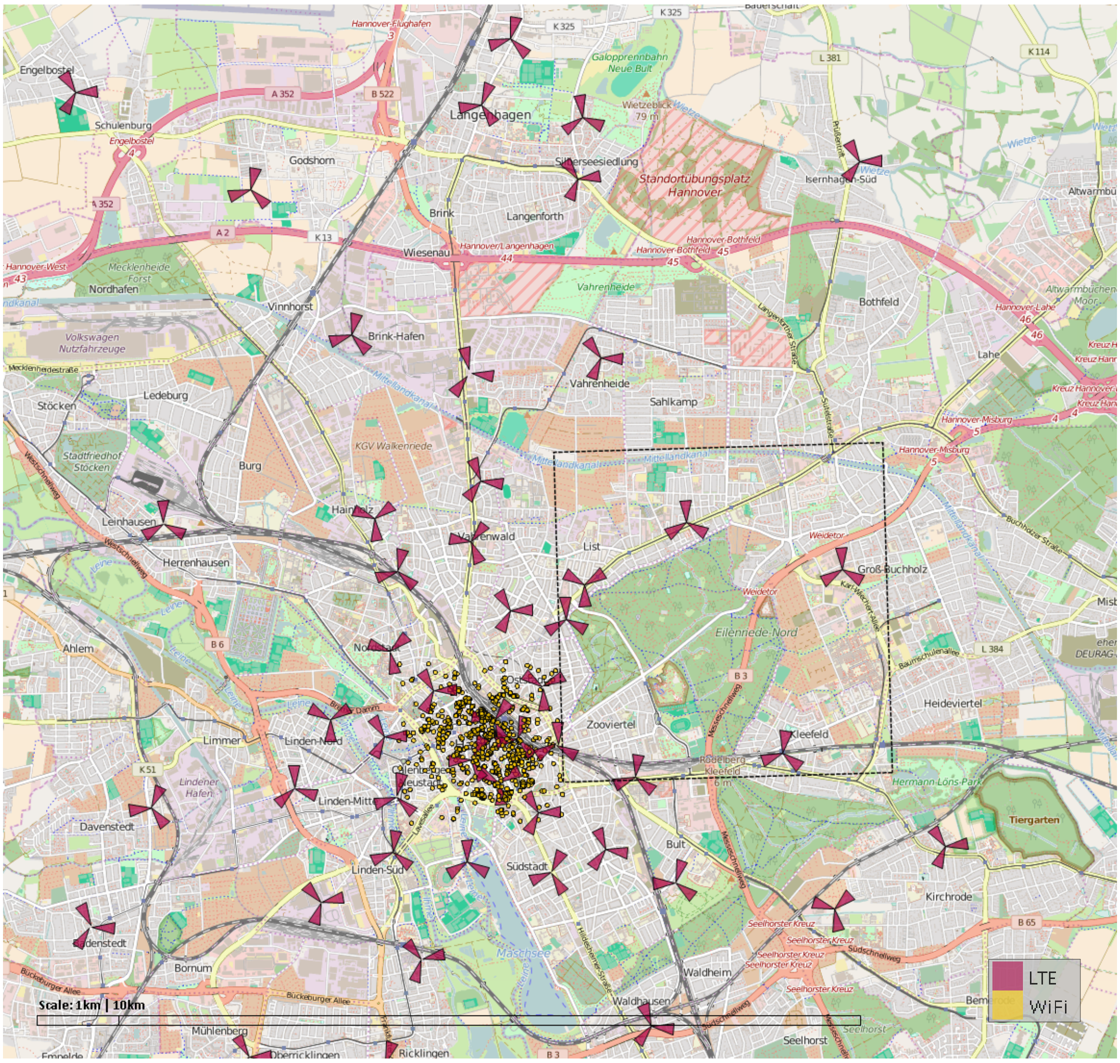


Figure 4.15: Scenario B: *Rural location, Normal mobility profile (RN)*

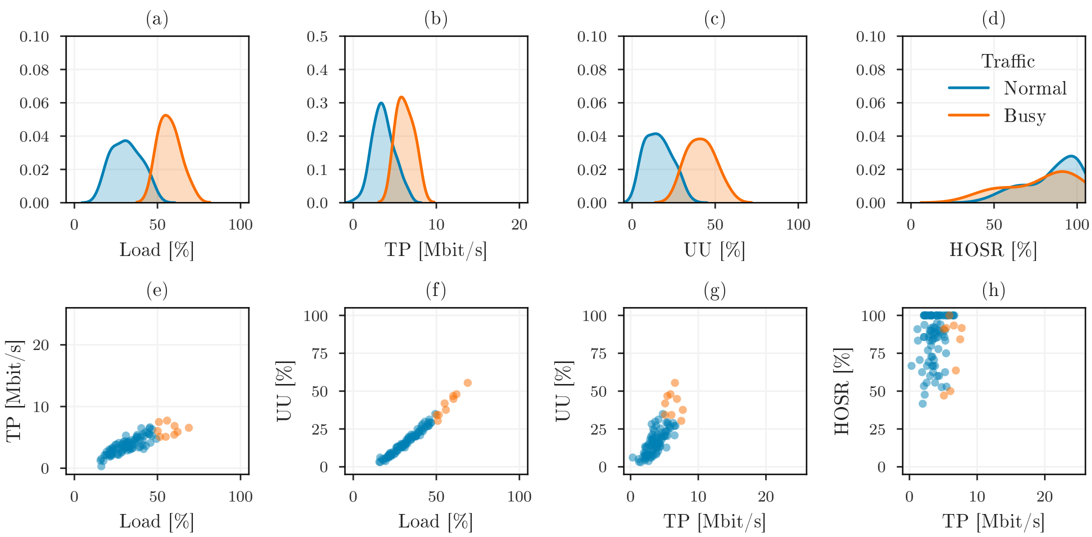


Figure 4.16: KPIs for scenario B, divided into traffic conditions

4.2.4 Scenario C: *Rural Location with a High-Speed Mobility Profile*

The next scenario is covering a major highway (the Autobahn "A2"), located north of the inner city of the "Urban Hannover Scenario". Users with a high velocity are travelling on the highway tracks (cf. subsection 3.1.6). Because this simulation area is not located in the inner city, no small cells are part of the mobile network either. All relevant scenario parameters are summarised in Table C.3. The relationships and KDEs for the four KPIs are in Figure 4.18. The overall performance features, in general, a similar behaviour compared to the KPIs presented previously in subsection 4.2.3. This is due to the nature of the same cell locations. Both scenarios mainly cover rural cells. However, the main difference is that the majority of users here are travelling at a high velocity. The speed and the aim-oriented trajectories, as introduced in subsection 3.1.6, lead to an overall degraded QoS and QoE. For example, the HOSR, shown in subplot (d), feature a rather good performance for both data traffic conditions at first sight. A closer look, however, reveals that the KDEs cover a rather large span compared to results from previous scenarios. This range indicates a bad HOSR performance for some cells in the network.

On the whole, this scenario is comparable to the one just introduced. The data traffic distributions are similar. Even though, the HO behaviour differs in a way as this scenario exhibits a degraded performance due to the high-speed users in the system.

4.2.5 Scenario D: *Large-Scale Network for Reference and Evaluation*

Finally, this last scenario covers a greater area of Hanover and is considered to be a *large-scale, multi-layer and multi-RAT* network scenario. The boundaries of the defined region, as well as the previous ones using a light grey, are shown in Figure 4.19. 1000 cells in data are located in this scenario – 195 LTE macro and 805 WiFi small cells. It includes urban areas, e.g. the inner city with a high cell density, and rural ones, e.g. in the northern and eastern part with a rather sparse cell density. The motorway "A2" (see also scenario "C" in subsection 4.2.4) can be found in the northern part of the region as well. User movements are simulated including all kinds of mobility models – from rather static indoor users in buildings, up to high-speed vehicles travelling on the motorway. All technical parameters are summarized in Table C.4. Figure 4.20 again gives an overview of the KPI behaviour for this scenario. The KDE plots (a), (b) and

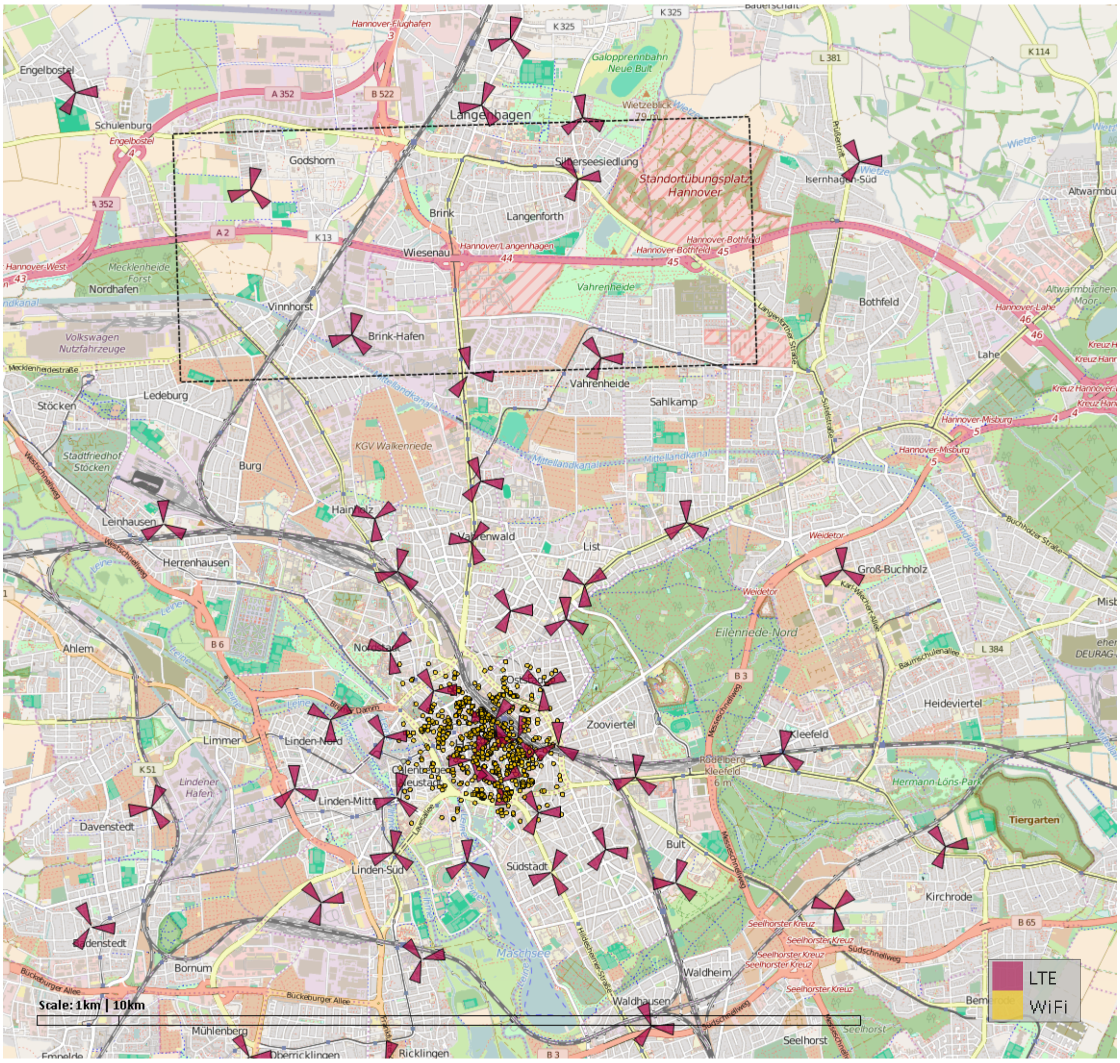


Figure 4.17: Scenario C: *Rural location, High-speed mobility profile (RH)*

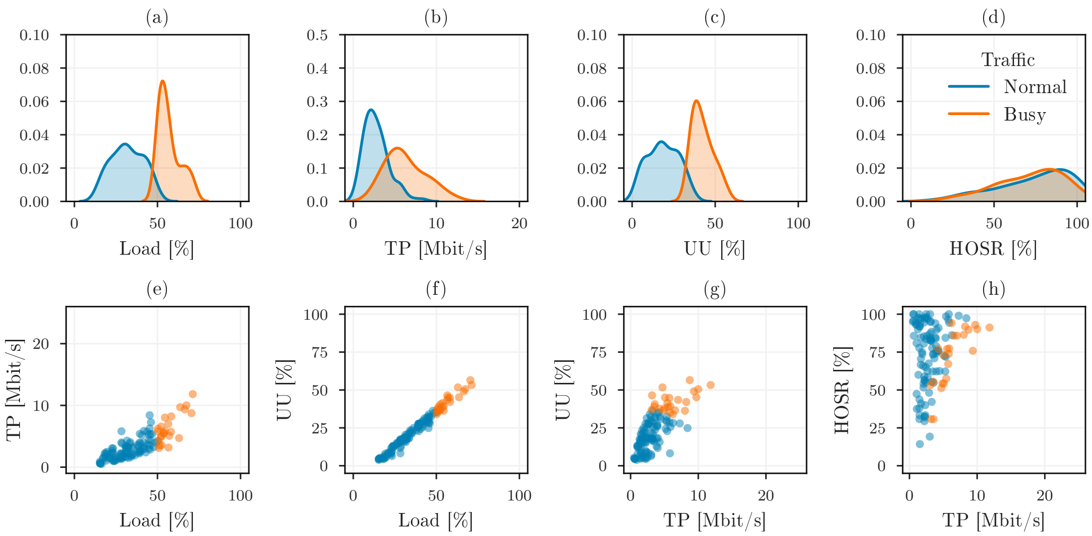


Figure 4.18: KPIs for scenario C, divided into traffic conditions

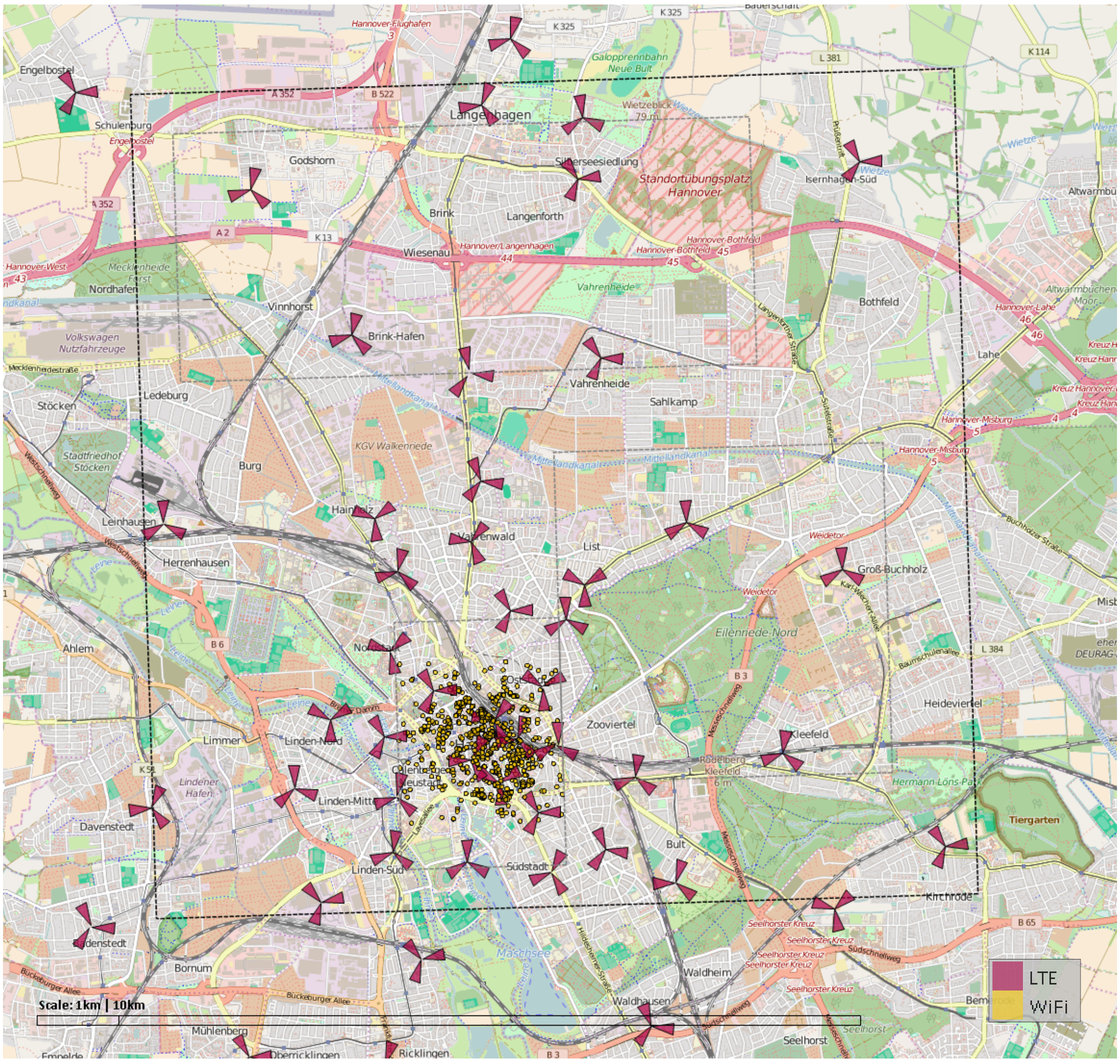


Figure 4.19: Scenario D: *10 km × 10 km Reference and Evaluation Scenario (10x10)*

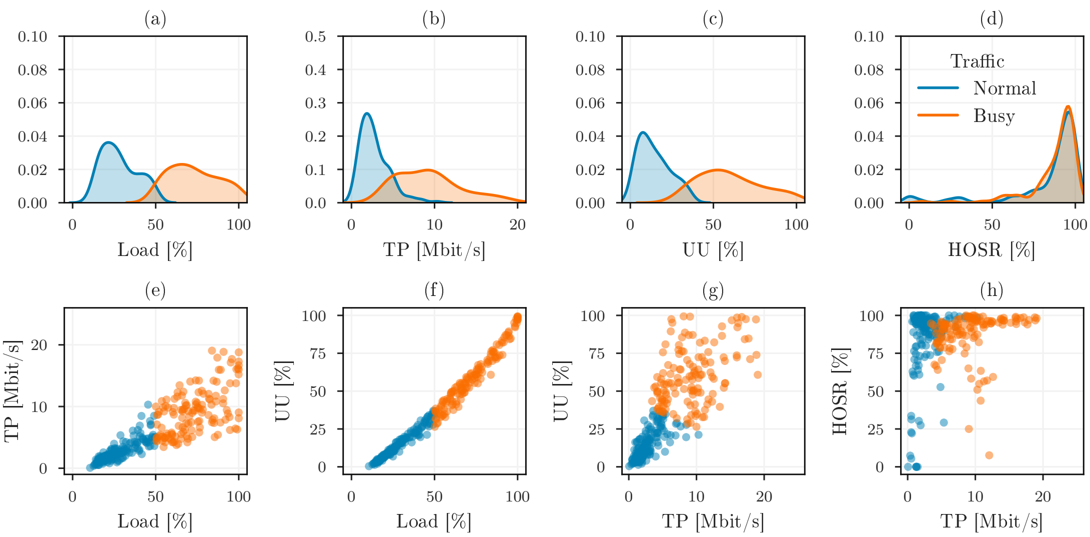


Figure 4.20: KPIs for scenario D, divided into traffic conditions

(c) reveal that the scenario is working at capacity. Cells in normal, as well as cells in busy hour traffic conditions, contribute to the overall network performance. Again, a similar behaviour regarding the relationship of cell load and the fraction of unsatisfied users can be seen (subplot (f)). It becomes more likely for a user to be unsatisfied when connected to a cell with a high load. This performance is as expected as well. The HOSR behaviour, see subplot (h) of Figure 4.20, shows different characteristics. First, the overall performance seems to be rather good. This is in line with previous results from Figure 4.14 to Figure 4.18. In contrast, a few cells with a low load level feature a bad HOSR performance. However, since this scenario also features WiFi APs a bad HOSR behaviour can be expected (see also results from Figure 4.14).

In brief, this scenario represents a large-scale, sophisticated mobile radio network. The KPI characteristics reflect different aspects that are also covered by the previous scenarios.

4.3 Concluding Remarks

This chapter explained the concept of context attributes for cells in the mobile network. Moreover, a method to identify and derive cell classes based on geographical data is introduced. After that, different scenarios are defined that focus on selected cell classes and, thus, feature different context attributes. A listing of the covered cell classes (cf. section 4.1) by the various simulation scenarios (cf. section 4.2) can be found in Table 4.3. Detailed summaries of the relevant technical parameters for each scenario are presented from Table C.1 to Table C.4 in the appendix. All areas are a subset of the “Urban Hannover Scenario”. Other realistic scenarios are available as well (for instance [Möl+15]) but are not as complete and do not cover such a large area as this one.

Table 4.3: Covered cell classes (see Table 4.1) by the defined simulation scenarios

Scenario	**Class ID**							
	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*
A	✔	✔	✔	✔				
B					✔	✔		
C							✔	✔
D	✔	✔	✔	✔	✔	✔	✔	✔

Furthermore, Figure 4.21 shows the (fluctuating) total number of active users in the areas of the different scenarios for time step of the given simulation runtime of

3 h. Please note that the dips in the curves are due to the available user trajectories. The trajectories used are (usually only) generated for a simulation time of 1 h. So to simulate three full hours multiple trajectories need to be copied, shuffled and shifted to a later starting point accordingly – leading to *fluctuating* amount of total subscribers in the system and longer possible simulation time.

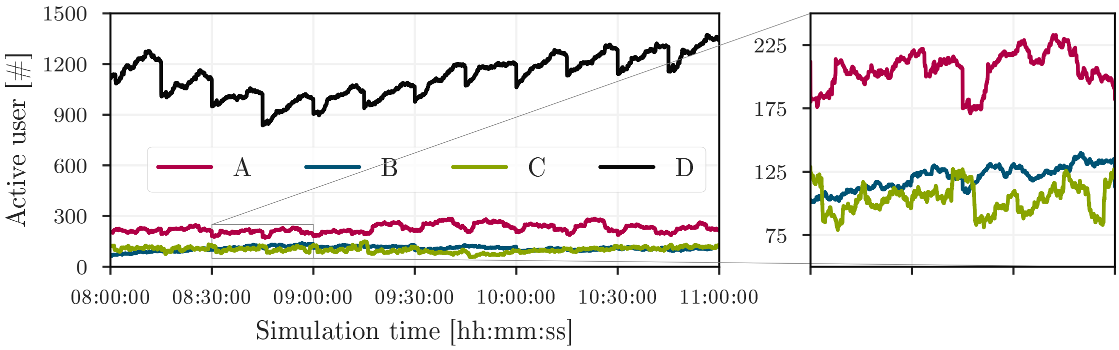


Figure 4.21: Number of active users in each scenario

All relevant scenario and (default) parameters for the following investigations are summarised in Table 4.4. In general, realistically planned LTE macro cells and small WiFi APs are considered. A 3D ray-optical path loss prediction model [Kür99] with a spatial resolution of 10 m × 10 m for LTE and 1 m × 1 m for WiFi is used. Since only a microscopic user mobility mix is taken, a data traffic model with different service types is defined (cf. Table 4.2). Signalling traffic, e.g. due to HO commands, is reflected by setting a background load value for each cell at 10 % [Jan16, p. 58]. To capture the scenario characteristics and to collect enough KPI statistics for the respective SON functions evaluation, the simulation time covers a rather large time span of 3 h. With a temporal resolution of 100 ms, this adds up to 108,000 consecutive simulation steps. Finally, the three SON functions change four cell parameters:

- The CIO (configurable by the LB function) is set at 0 dB for all cell combinations. This means, no initial data traffic off- or on-loading is configured. This was also the approach of [Lob+10].
- The HO HYS and TTT value pairs (configurable by the RO function) are all set at 6 dB and 300 ms, which is (roughly) in line with the default settings of [Jan16, pp. 143] and both EU FP7 projects SOCRATES [Kür+10, p. 81] and SEMAFOUR [Hah+15b].
- The RSS selection threshold (configurable by the TS function) is set at -70 dBm, which is in accordance with, e.g., [Kov+14] or [Wan+14].

Table 4.4: Scenario and simulation parameters for the SON performance and network management investigations

Category	Parameter	Value	Reference
Network	Radio Access Technologies (RATs)	LTE and WiFi	[Ros+16a] and [Ros+13a]
	Network layers	Macro- and small cells	
Predictions	Path loss prediction model	3D ray-optical	[Kür99] and [KM02]
	Spatial resolution	$1\,\mathrm{m} \times 1\,\mathrm{m}$	
Data Traffic	Traffic model	Session call model (based on Table 4.2)	[Irm+08] and [ETS97]
	Background load (due to signalling traffic)	10 %	[Jan16, p. 151]
Time	Simulation time	3 h	
	Temporal resolution	100 ms	[Jan16, p. 58]
Default Parameters	Cell Individual Offset (CIO)	0 dB	[Lob+10] and [Kür+10]
	Handover (HO) Hysteresis (HYS)	6 dB	[Jan16], [Jan+10] and [Kür+10]
	Handover (HO) Time-To-Trigger (TTT)	300 ms	[Jan16], [Jan+10] and [Kür+10]
	Received Signal Strength (RSS) threshold	-70 dBm	[Kov+14] and [Hah+15b]

Chapter 5

The Impact of Realistic Network Scenarios on SON Functions

The original concept of Self-Organising Networks (SONs), especially in the domain of self-optimisation, was to monitor KPIs in the mobile system and dynamically adapt (radio) parameters based on specific (SON) algorithms. As described in chapter 2, these algorithms work with internal methods, thresholds, step sizes, etc. Typically, the above-mentioned SON specific parameters – the so-called SON Function Configuration Parameters (SCPs) – are set by the vendors to default SON Function Configuration Values (SCVs) and are usually *not* altered by the MNO. Figure 5.1 visualises the connection between SCPs and SCVs.

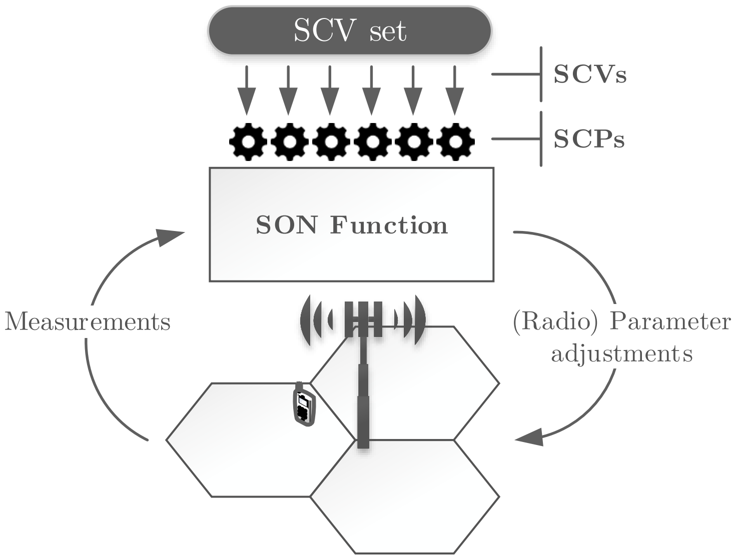


Figure 5.1: SCPs and SCVs

In contrast to default SCVs, set by the vendor of such SON functions, the MNO *now* needs to adjust each SON function individually and in a way that the outcome of the parameter adjustments leads to the desired network behaviour by changing these SCV sets. For that, the impact of different SCVs for various SON functions has to be investigated in order to know the *effect* on the different KPIs. Previous works have shown that the actual configuration of the SON function and the appropriate adjustment with the right SCV set can have a profound impact on the performance of the network (see [Hah+14] and [HK14]). The following extensive simulations go a step further by testing multiple SON functions in different network environments. For that, the three SON algorithms are trialled in the three testing scenarios (scenario *"A"*, *"B"* and *"C"*, as defined in section 4.2). The trialling is achievable by simulating the SON functions in the scenarios with different SCVs. The actual SCVs used are based on reasonable and logical SCP combinations from previous publications and can be looked up in Table A.1, Table A.2 and Table A.3 in the appendix, respectively.

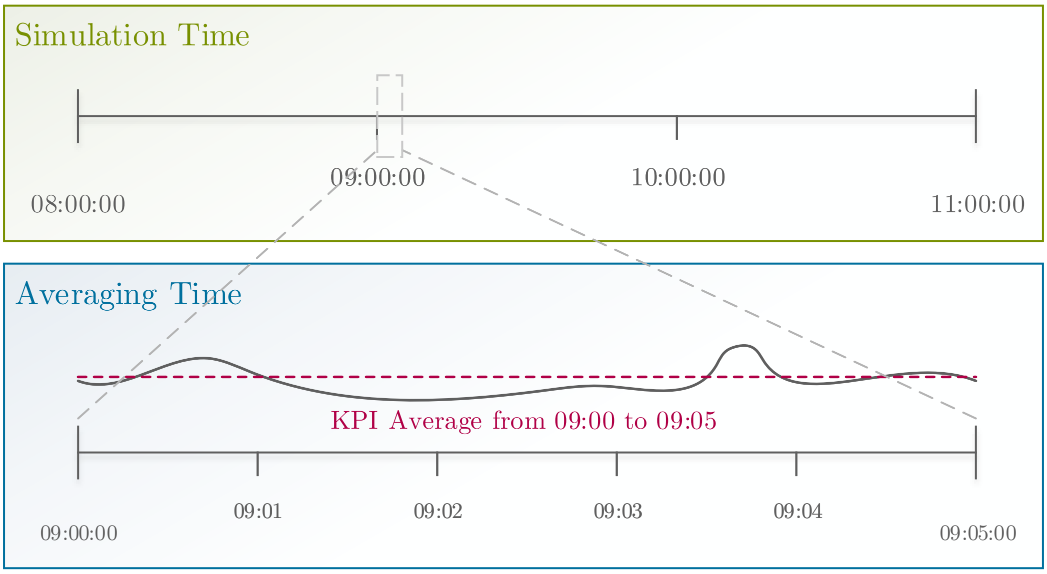


Figure 5.2: KPI averaging over the simulation time

For that, the LB (using the colour *orange* in the following, see e.g. Figure 5.3 to Figure 5.5) and RO (using *yellow*, see Figure 5.6 to Figure 5.8) are tested in all scenarios. The TS (using *blue*, see Figure 5.9) is only considered in the first scenario ("A"), because TS here requires two RATs to steer the user data traffic from one technology to another. Only this test scenario – and the final evaluation scenario ("D"), used in the next chapter – features two technologies. As already stated in section 4.2, the simulation time for each SON function with its SCV sets is set at 3 h to collect enough KPI statistics. Moreover, to mimic a realistic network operation, KPI measurements are aggregated and processed for a given time interval of ten minutes, leading to 18 sampling points for each cell in the network [Kre06, p. 55]. Figure 5.2 illustrates the process. Additionally, box plots represent each SCV set as well as the baseline to assess the SON performance. The box plot itself shows the quartiles of the datasets and the median, indicated as a line inside the box. Outliers, i.e. data samples that are outside the 25^{th} and 75^{th} quantile, are represented by small dots [VH81, pp. 65].

5.1 LTE Load Balancing

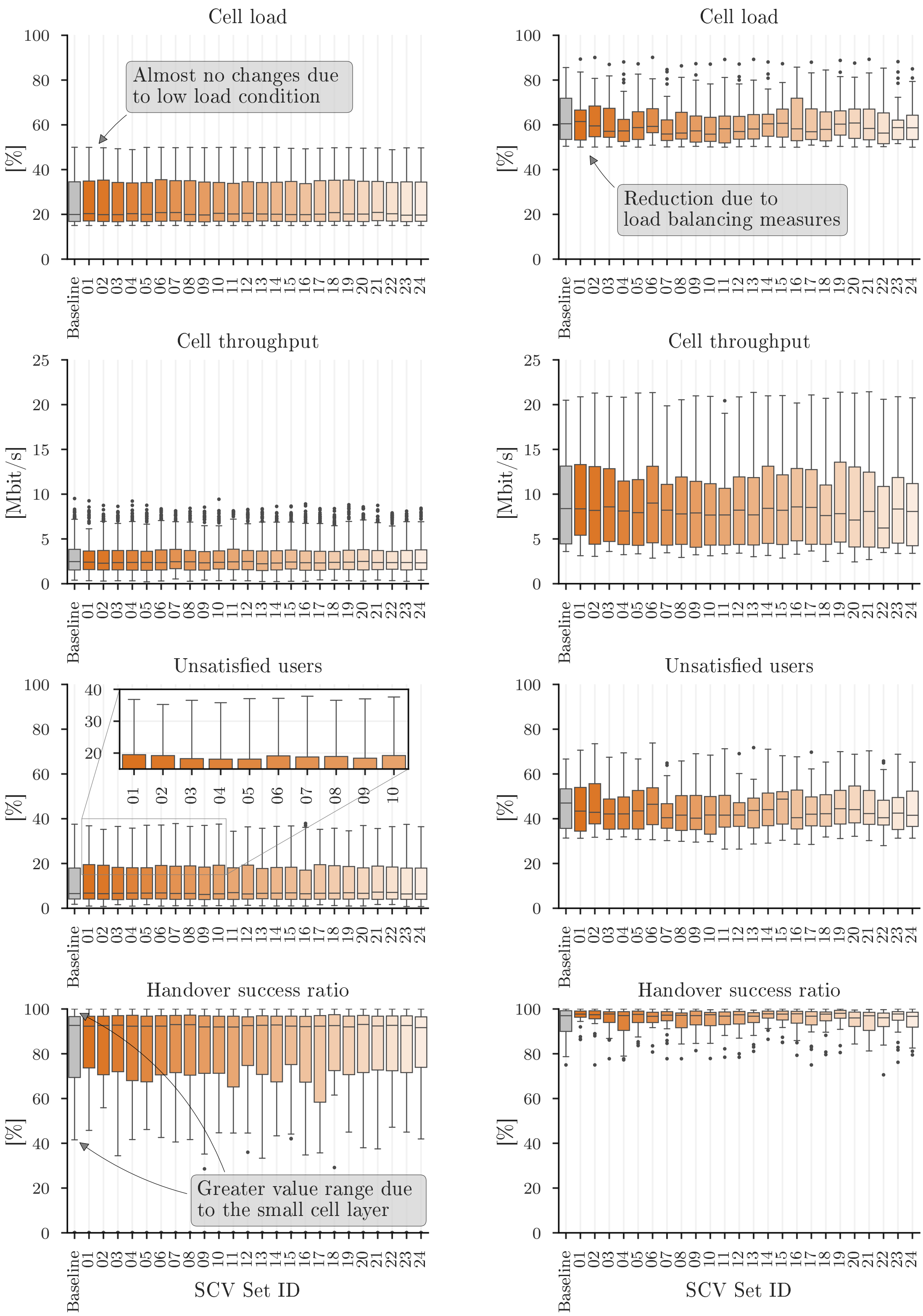
This section investigates the Load Balancing (LB) SON function in the three different environments. For that, the LB SCV set combinations are compared against a baseline scenario. This reference is simulated by using the default (radio) parameters specified in Table 4.4 with no SON functionality active.

Scenario A: *Urban Location, Normal Mobility Profile*

Figure 5.3 shows the SCV set performances for the four KPIs, divided into normal (Figure 5.3a) and busy hour (Figure 5.3b) traffic conditions. At first glance, no drastic KPI changes are observable by varying the SCV set and, thus, the configuration of the SON algorithm itself. This is especially true when focusing on the normal hour traffic condition. Such results are as expected, because the cell load values here are rather low on average, which do not require LB actions in the first place. Cells operating in the busy hour display a more diverse behaviour for different LB SCV sets, which is noticeable for the cell throughput and the fraction of unsatisfied users. For example, SCV set "06" can improve the cell throughput concerning the median and slightly on the 75^{th} percentile, whereas other SCV sets, e.g. "22", actually degrade the performance. When looking at the median values for the performance of unsatisfied users, it is perceptible that LB can reduce the fraction and thus improve the QoE for the users for almost all SCV settings. A reason that the LB is not capable of improving the KPI behaviour further is the actual scenario setup itself. The presence of hundreds of WiFi APs, a relative small inter-site distance from the LTE cells and, hence, at a rather high interference level limits the ability to offload to other cells.

Scenario B: *Rural Location, Normal Mobility Profile*

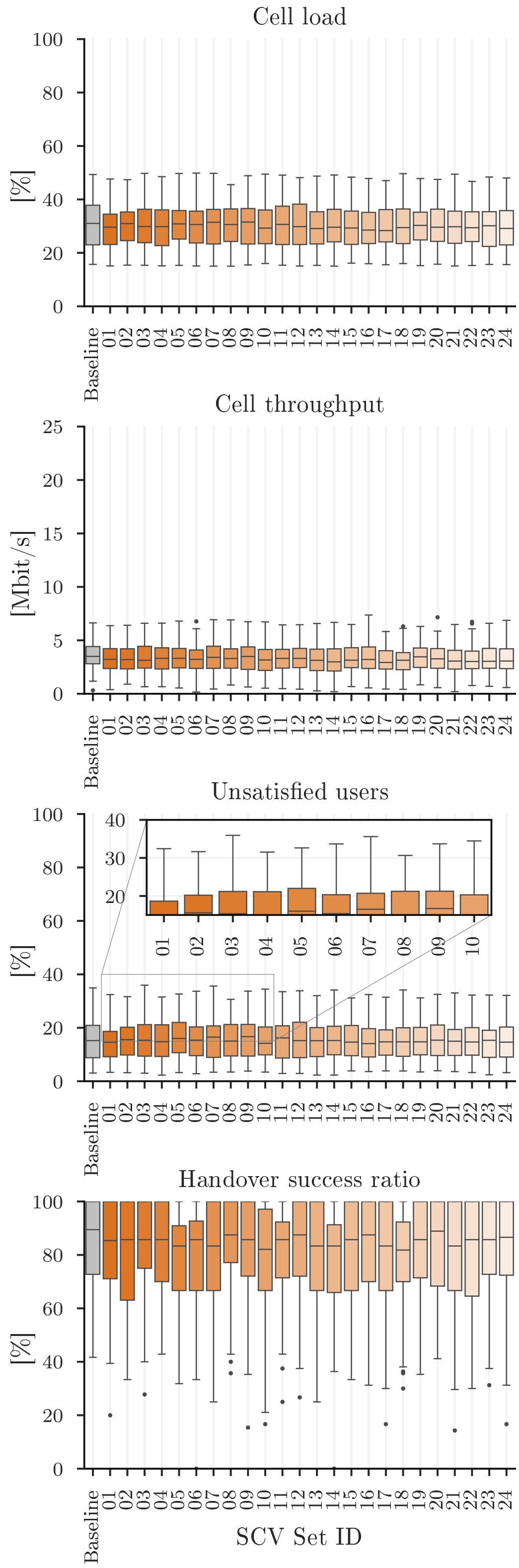
Figure 5.4 considers the same SCV sets, but this time for scenario "B". As a reminder, this scenario features a rural environment with a normal mobility mix, i.e. no



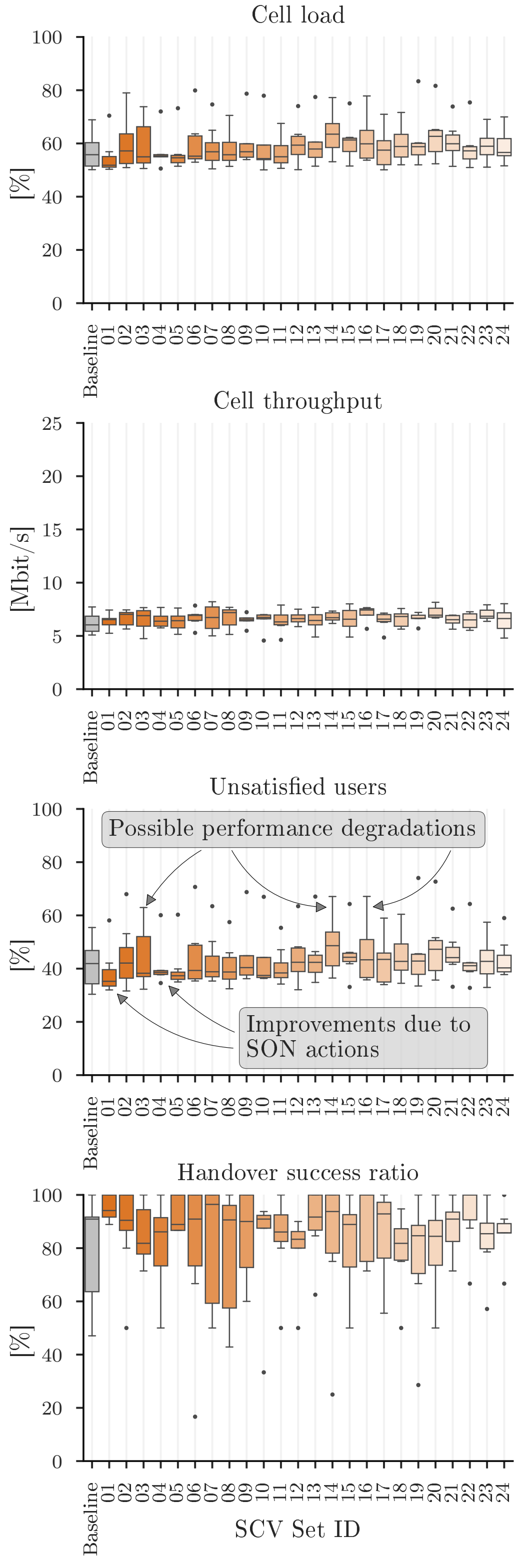
(a) Normal hour

(b) Busy hour

Figure 5.3: LB SCV set performance: *Scenario A*

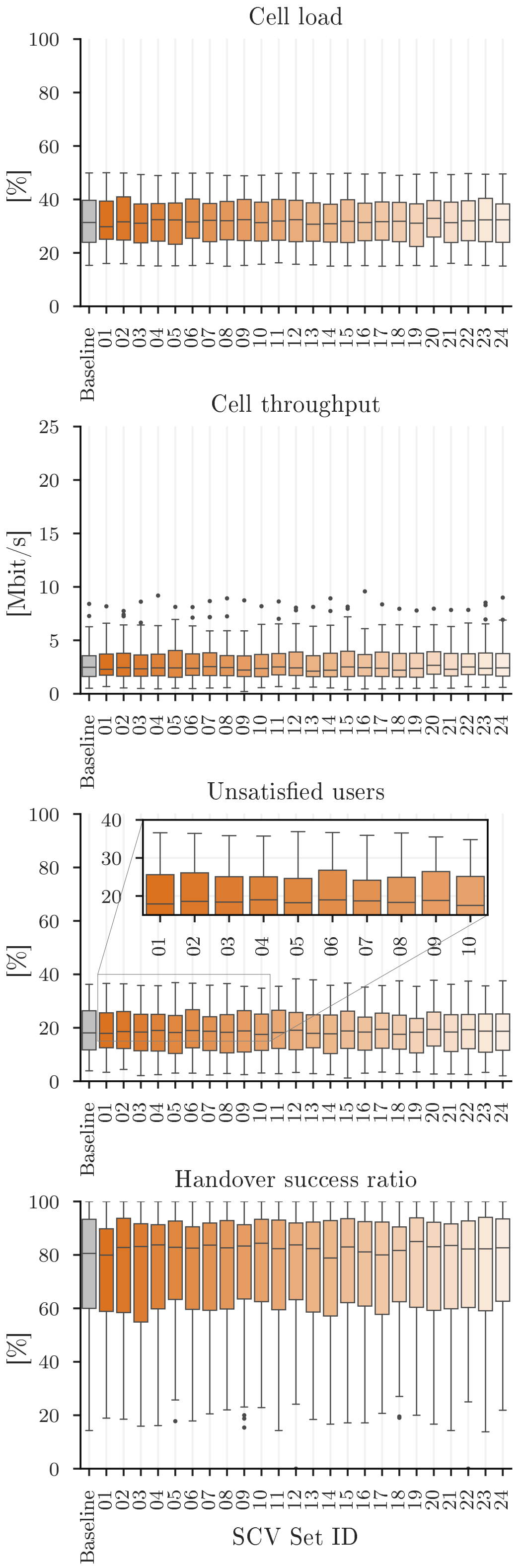


(a) Normal hour

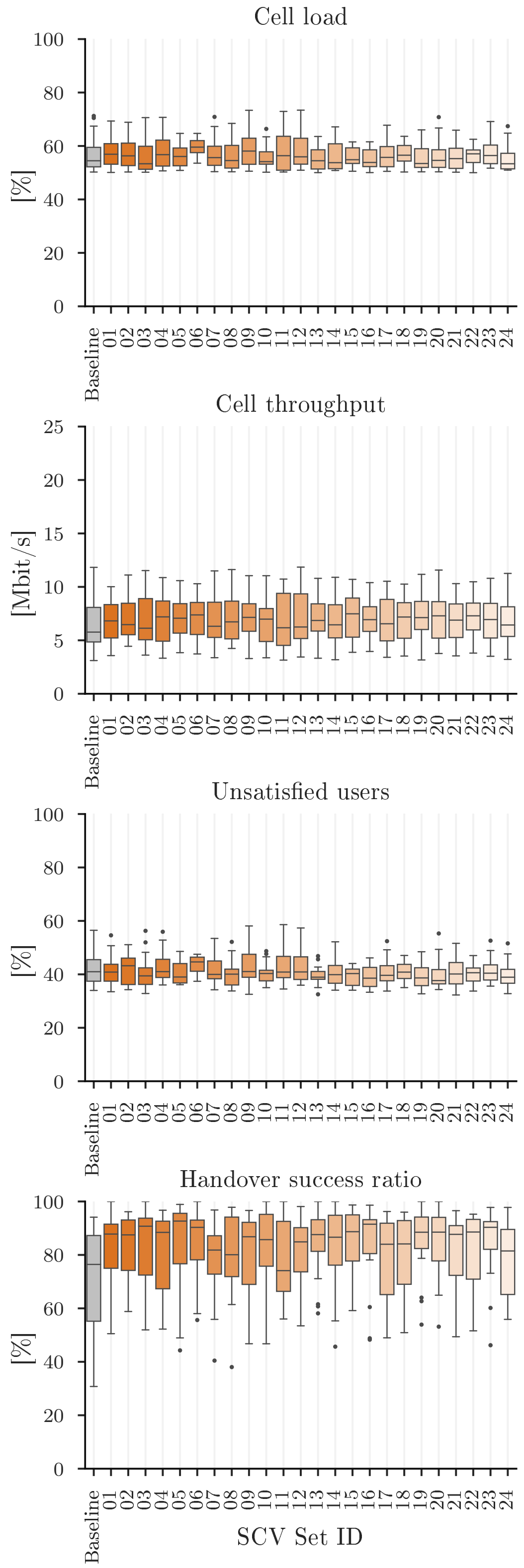


(b) Busy hour

Figure 5.4: LB SCV set performance: *Scenario B*



(a) Normal hour



(b) Busy hour

Figure 5.5: LB SCV set performance: *Scenario C*

specific high-speed users. The results are again separated into two traffic conditions: Figure 5.4a shows cells running at a normal hour, Figure 5.4b in the busy hour. The performance of the different SCV sets in normal traffic conditions is once more like the previous scenario, cf. Figure 5.3a. The load in the cells is small, so the LB does not have to react and change parameters in the system very often. Yet, the HOSR differs because, if the LB reacts, the CIO parameters get changed. The CIO has a direct impact on the HO decision and thus changes the HP. Since the load is small, only a few CIO parameter adjustments are made. Nonetheless, these changes affect future HO decisions as well. Greater differences are observable for cells operating in the busy hour, cf. Figure 5.4b. The cell loads increase in many cases. This behaviour is explainable by the SON actions of the LB function. If a cell is in an overload situation, the LB function will try to shift users to less loaded neighbouring cells. This will usually lead to degraded path loss and interference conditions. The consequence is a higher demand for cell resources to satisfy the requested data rates, leading to higher cell loads in general. The increase of the cell load is accepted, as long as the overall goal of the LB function is fulfilled: to improve the QoE for the users in the system. As explained before, the fraction of unsatisfied users is a measure for QoE, so the goal is to decrease the fraction. However, this is not observable for every SCV set. Why this is not feasible for many SCV sets is explainable by, again, having a look at the scenario itself (see subsection 4.2.3 and especially Figure 4.15). Since the cell locations are chosen to be in a rural environment, the inter-site distances are larger compared with an urban scenario. This does not fundamentally limit the ability to offload traffic to neighbouring cells but makes it difficult to set the appropriate CIO values. In the same way, the HOSR performance in the busy hour also indicates that behaviour. A lot of SCV sets cause a degradation of this very KPI.

Scenario C: *Rural Location, High-Speed Mobility Profile*

Finally, Figure 5.5 covers the SCV set performance for a rural environment with a predominant high-speed user profile, i.e. scenario "C". As explained in subsection 3.1.6 and with Figure 4.18, this environment features a rather bad HOSR performance due to the high velocity of the users. Such behaviour is also detectable for the different SCV sets. Both traffic conditions (Figure 5.5a and Figure 5.5b) also display a similar behaviour compared to the previous results shown in Figure 5.4. This is a strong indication of the influence of the cell location on the actual LB performance because of the larger inter-site distance of the cells and the sparse density compared to the one in scenario “A”. As a result, a first general observation is that not every SCV set necessarily leads to a better KPI behaviour.

5.2 LTE Robustness Optimisation

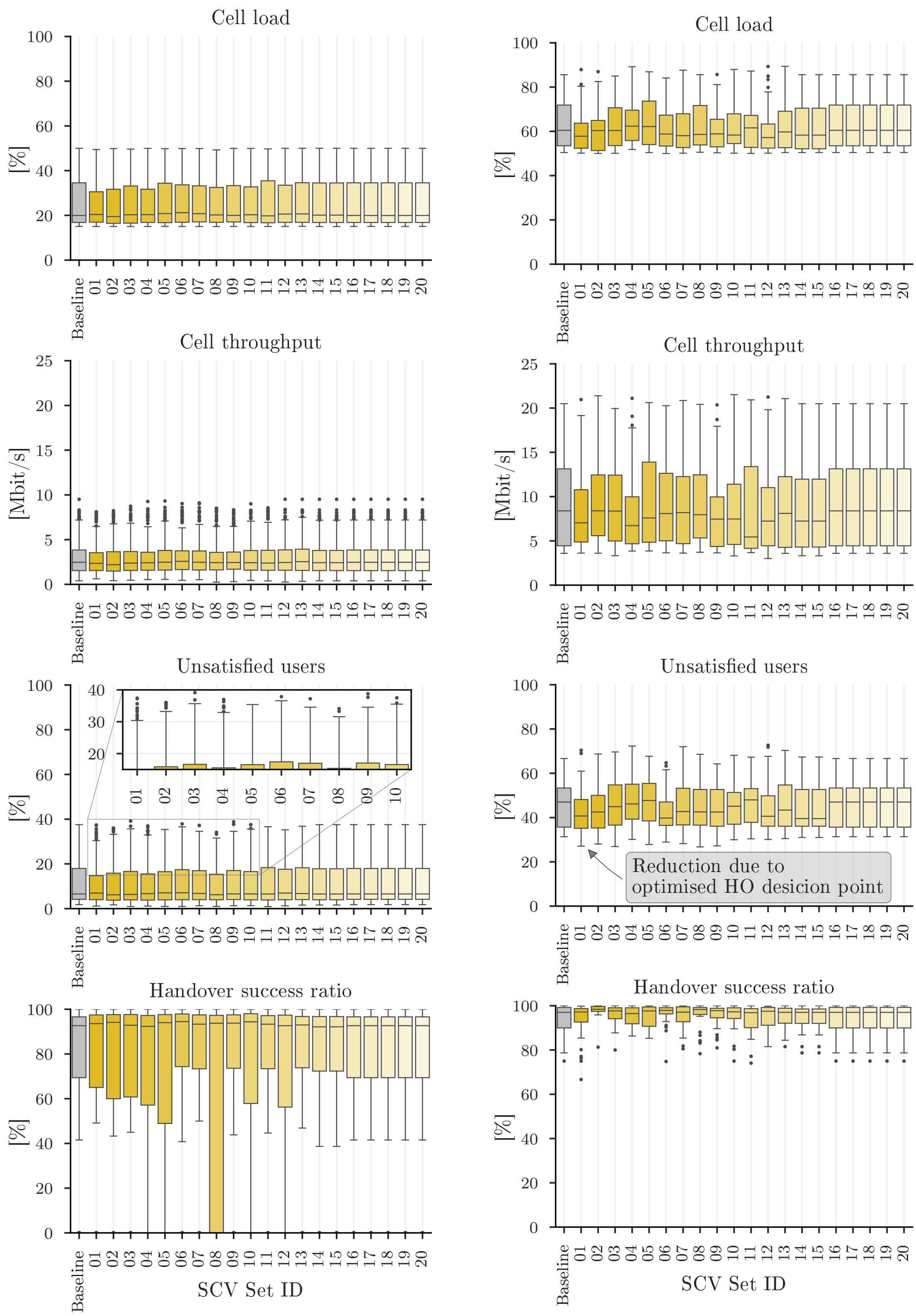
This section focuses on the SCV set performance of the Robustness Optimisation (RO) SON function. Again, the SON function is tested in the three scenarios defined in section 4.2. As described in subsection 2.2.2, the main goal of RO is to improve the QoS for the users in the system by adjusting the HO decision point, i.e. HO Hysteresis (HYS) and Time-To-Trigger (TTT) value pairs. Consequently, the focus lies on the HOSR performance metrics.

Scenario A: *Urban Location, Normal Mobility Profile*

Figure 5.6 shows the SCV set performances for the first scenario – the same as in Figure 5.3, but this time only the RO SON function is enabled. Both traffic conditions, i.e. the normal hour presented in Figure 5.6a and the busy hour in Figure 5.6b, feature a similar behaviour. In both cases, the HOSR is already quite high in the baseline scenario, i.e. without any SON function active. This KPI behaviour does not change drastically for the remaining SCV set as well. The fraction of unsatisfied users decreases as a positive side effect as well. The adjusted HO decision points lead to a different cell load behaviour because users will connect sooner (or later) to other cells leading to improved interference situations. Again, the degraded HOSRs in the normal hour are due to the presents of the WiFi APs with the small cell sizes.

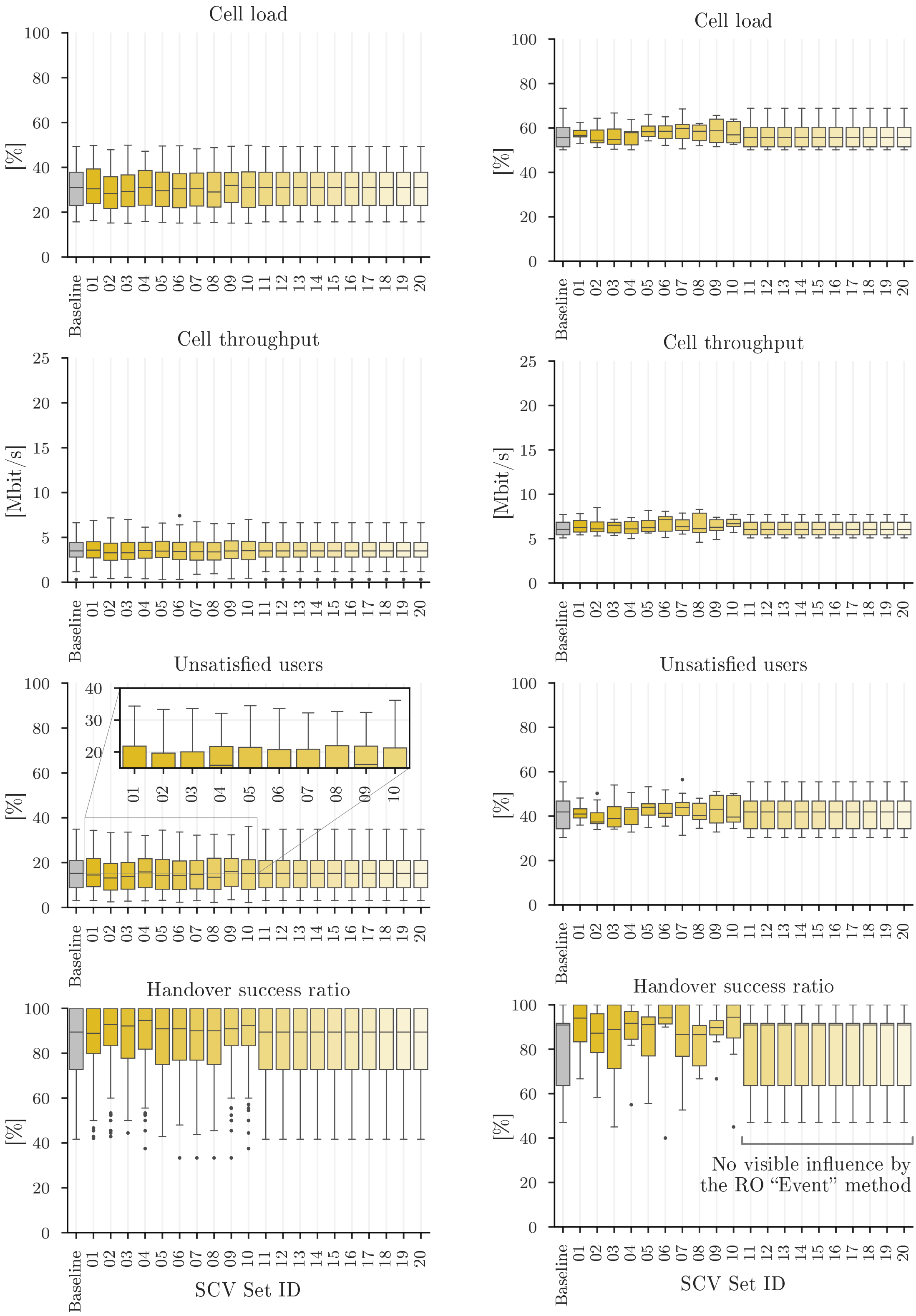
Scenario B: *Rural Location, Normal Mobility Profile*

The impact of the rural scenario on a normal mobility profile can be found in Figure 5.7. The KPI behaviour is similar compared to previous scenarios, meaning that the HOSR is already high, even in the baseline simulation. The RO function can boost this performance only in a few cases, i.e. with selected SCV sets. See for example SCV set “04” or “10” in the normal hour (Figure 5.7a). The reason for that is the absence of negative HO events, such as HOFs or RLFs. Without such events, the RO function does not need to change the (default) parametrisations of the HYS and TTT values. Having a closer look at the busy hour, a couple of SCV sets improve the HOSR performance in a more distinct way. Namely SCV set “06” or “09” lead to a considerably HOSR improvement regarding the median, but also the outliers (Figure 5.7b). On the other hand, SCV sets from “11” to “20” do not seem to influence the KPI behaviour at all. This fact is taken up once again when discussing the following scenario.



(a) Normal hour **(b)** Busy hour

Figure 5.6: RO SCV set performance: *Scenario A*



(a) Normal hour

(b) Busy hour

Figure 5.7: RO SCV set performance: *Scenario B*

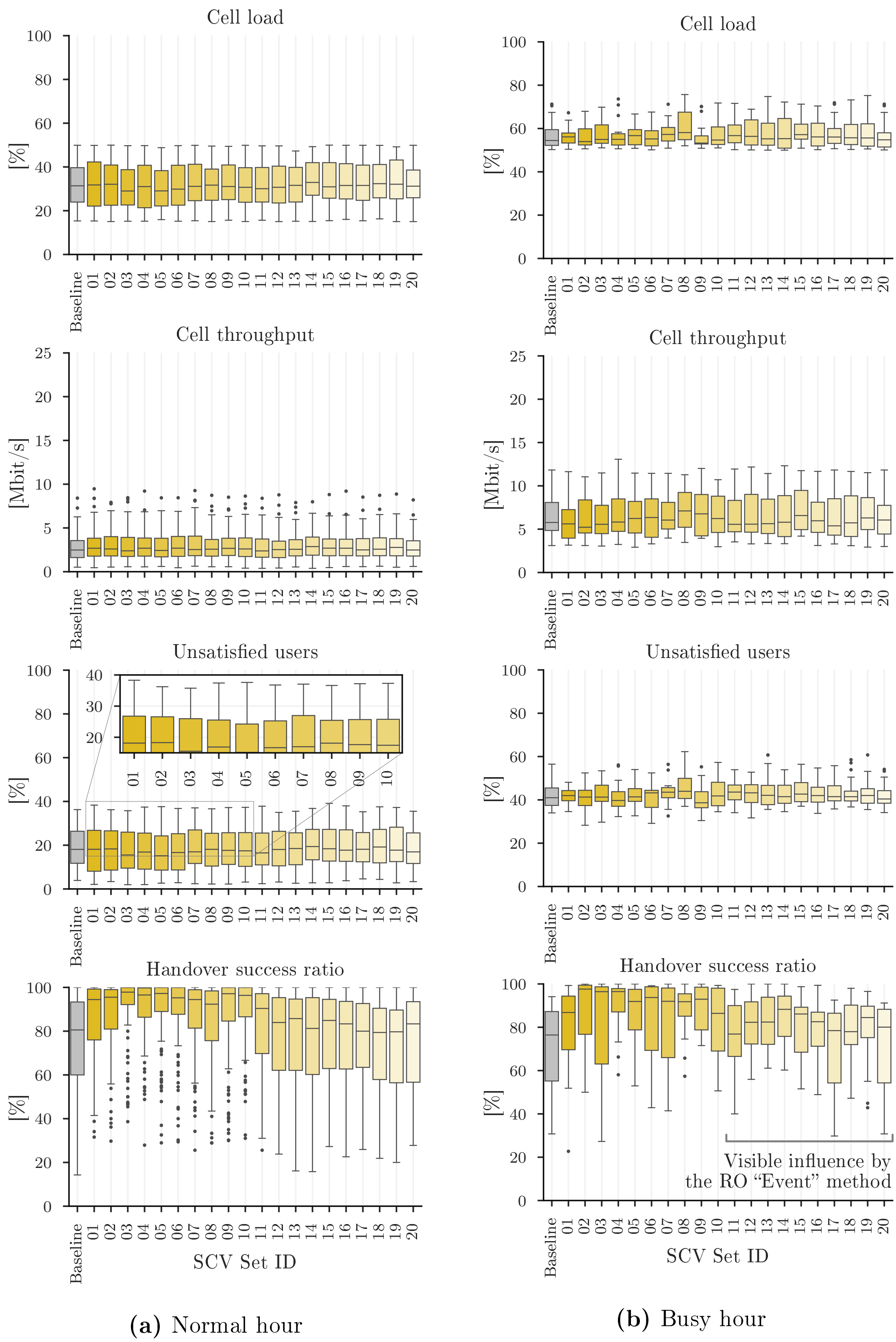


Figure 5.8: RO SCV set performance: *Scenario C*

Scenario C: *Rural Location, High-Speed Mobility Profile*

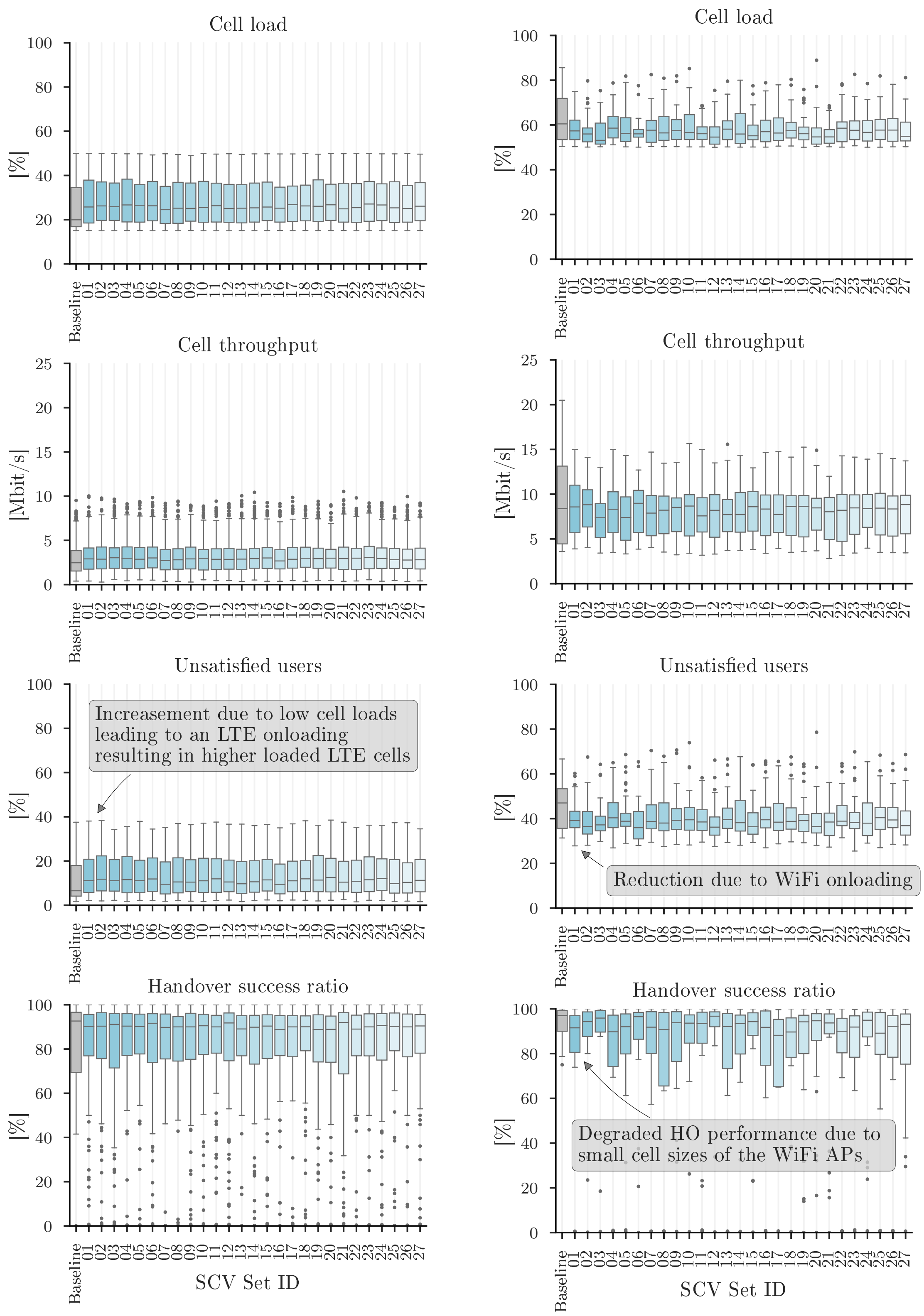
Finally, Figure 5.8 presents the SCV set performance for scenario "C" – featuring rural cells and a predominant high-speed mobility mix. Due to the latter, the baseline in this scenario shows a rather worsened HOSR performance, in contrast to the two previous scenarios. For both traffic conditions, see the normal hour in Figure 5.8a and the busy hour in Figure 5.8b, the RO SON function is able to improve, partly even drastically, the HOSR performance. See for example SCV set ID "03", "09" and "10" in Figure 5.8a, or "02", "04" and "08" in Figure 5.8b. Compared with the previous environments, the SCV sets from "11" to "20" are now also impacting the HOSR performance. Such SCV sets let the RO function work with an "event-based" method (compare also Table A.2). Since high-speed users tend to produce more HO related events the RO functions can also adjust HYS and TTT values with this method. Note that this event-driven approach can lead to improvements of the KPI performance as well. This is another strong sign that the actual environment can have a profound impact on the SON functions and the underlying SCPs.

5.3 LTE/WiFi Traffic Steering

Lastly, this section lays out the impact on the KPIs for varying SCV sets for the Traffic Steering (TS) SON function. As described in subsection 2.2.3, the aim of the TS is to steer the traffic to an appropriate RAT to provide an improved QoE for the users. A special emphasis also lies on the HOSR since small cells usually degrade this performance. The evaluation of the impact only focuses on scenario "A", because WiFi APs are essential for that. Figure 5.9 shows the results.

Scenario A: *Urban Location, Normal Mobility Profile*

Related to the LB SON function, the main KPI focus is on the fraction of unsatisfied users. For cells operating in the normal hour, see Figure 5.9a, the changes are marginal. TS works with cell load thresholds for both RATs to decide when and how to steer users towards a specific technology. If the cell load is low, the algorithm only executes moderate RSS changes of the APs. The full potential of TS unfolds, likewise the LB function, in situations with heavy data traffic demands. Figure 5.9b captures this situation, where results from a busy hour traffic condition are presented. For instance, SCV set ID "01", "03" or "06" are able to reduce the fraction of unsatisfied users considerably. On the other hand, when offloading to WiFi APs, the HOSR performance degrades compared to the baseline scenario. That is because (small) cells



(a) Normal hour

(b) Busy hour

Figure 5.9: TS SCV set performance: *Scenario A*

often feature sudden RSS variations due to the limited transmit power and obstacles, such as walls or doors in an indoor environment.

5.4 Concluding Remarks

After evaluating the three SON functions in different realistic mobile network scenarios, the following concluding remarks can be made:

- A first conclusion is that with different SCV sets, the impact on the KPIs differs as well. This observation is noticeable for all three SON functions, respectively. In consequence, the underlying algorithms depend on the actual SCPs, such as thresholds, step sizes or internal methods. So, the MNOs have to count on a provisioning of a detailed description of the used SON algorithm – which the vendor of such functions needs to deliver. In the same way, this is a crucial requirement to steer the network performance with the help of SON functions. If no SFPMs are available or if there is a lack of trust in the provided SON Function Performance Models (SFPMs), the MNO has to rely on its own KPI measurements to build up separate models as described in [LSH16]. This, however, comes with greater risks of altering the network towards an undesired performance due to uncertainties originating from the highly complex network topology.

- Secondly, the used SON functions behave differently in the two traffic conditions – normal and busy hour. Especially the LB and TS functions do not require many SON actions in the normal hour, due to the low load values of the cells – hence, the rather low impact. However, the RO also leads to a different KPI behaviour, which is also in line with the actual use case of SON when it comes to a network *optimisation*. The need of SON is first and foremost given when the mobile system is working at capacity. Here, the SON can free up additional resources by optimising the system and, thus, improve the overall network performance.

- Furthermore, each of the three scenarios impact the SON performance in a different way. For instance, when considering the LB function, the urban scenario does not offer many possibilities to offload the traffic to other LTE cells due to a high inference level. On the contrary, the rural situation with a normal mobility profile offers greater potential to offload users to neighbouring cells and therefore to reduce the fraction of unsatisfied users. This is a first indication that the setting of SCPs has to happen carefully and by considering the specific cell context information.

- Following the previous point, the same SCV set does not necessarily lead to the same KPI behaviour in diverse network environments. For example, by comparing a normal mobility mix with high-speed users, the HP can be entirely different (see also the mobility modelling simulation results of chapter 3). Hence, it seems to be of the utmost importance to configure SON functions with the right SCV sets in each network environment. A simple default SON parametrisation might not be sufficient when it comes to deploying MNO objectives. As a consequence, chapter 6 also studies the performance of default SCV settings.

- Finally, the impact on the KPIs appears to be minor or even contradicting for *some* SCV sets – for *each* SON function and in *all* network environments. This finding is also in line with the results presented in the PhD thesis of Thomas Jansen [Jan16, pp. 75], which focused on the HO decision in LTE. Results show much higher performance gains in the hexagon network with random walk users, compared with a realistically planned network with a realistic mobility mix. For that reason, the testing of the SON functionality should be done by using *realistic* simulations. Also, a (self-organising) network management system is inevitable to ensure a desired KPI behaviour and to guarantee the fulfilment of pre-defined MNO objectives.

Chapter 6

Self-Organising Networks – Management and Operations

The insights gained into the SON function performance in different network environments from chapter 5 can now be used to create SON Function Performance Models (SFPMs). These models are essential for a so-called Policy-Based SON Management (PBSM) method. With the SFPMs, appropriate SCV sets for each cell in the network can be assigned by a SON Objective Manager (SOM) entity. For that, a SOM combines KPI objectives – defined by the MNO – with the available SFPMs – provided by the vendor of the SON function. Figure 6.1 depicts a simple representation of this approach. Moreover, [Fre16, pp. 99] presents and thoroughly evaluates different versions of a SOM entity. However, the primary focus of this work is not to showcase different SOM versions, but to investigate the impact of adjusted and managed SON functions on a realistic network scenario. In other words, for reasons of simplicity, the selection of SCV sets rests upon a rather simple (PBSM) technique: repositories are used to store the SCV set performances containing information about the KPI impact on cell attributes (e.g. location, mobility type or cell size – see section 4.1). These repositories represent the SFPMs. A network entity has to determine the cell class (cf. Table 4.1) during run time. The cell class information is then mappable with the SCV set repositories. Finally, in combination with the formulated operator objectives, the SOM can determine and pass the right SCV sets to the cells/APs in the network, where the three SON functions run. Likewise the *altering* of the network performance by changing SCVs sets appropriately, the actual *impact* of SON function combinations is also of great interest. Usually, multiple SON functions all run in parallel at the same time. A simple assumption here is that the different SFPMs can easily be combined and the impact on the network is the same. These effects are still to be discussed and evaluated in a realistic network environment.

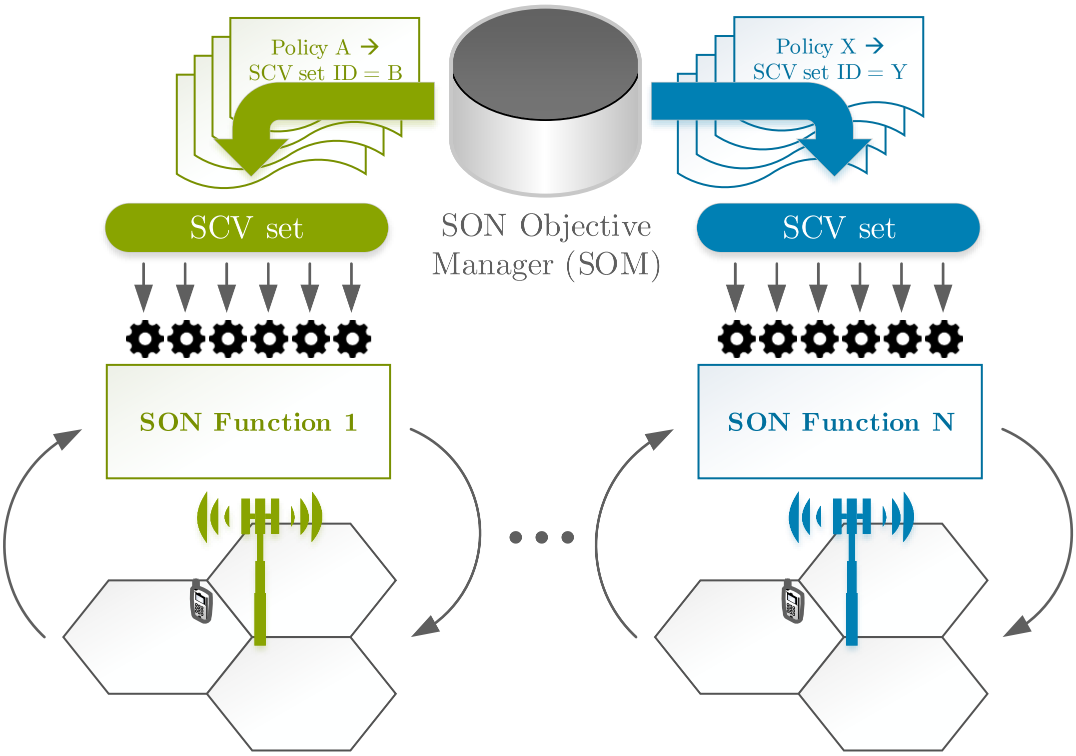


Figure 6.1: The setting of SCVs by a SOM entity

Thus, the structure of the next sections is as follows: section 6.1 gives more examples for network operator goals to further motivate the need for a (self-organising) network management system. The next section 6.2 uses such goals. Here, different (management) approaches are investigated and compared with each other. After that, section 6.3 studies the impact of different SON function combinations on the network performance. This knowledge is crucial to run a consistent SON orchestration system. The management layer introduced in chapter 1 (cf. also Figure 1.4) is summarised with all its components in detail in section 6.4. Additionally, recommendations are given how an MNO should run a SON-enabled system. Finally, section 6.5 recaps the scientific findings of SON management and operation, in the same way as it was done in all previous chapters. Please also note that this time only the large reference "Scenario D" (see subsection 4.2.5) will be used in order to conduct the various system-level simulations.

6.1 Examples for Operator Goals

The desire to keep OPEX as little as possible and to postpone CAPEX as long as necessary are just two major objectives an MNO has in mind. SON can help to reduce

Table 6.1: Network management evaluations

SON evaluation		**Operator objective**	
SCV settings	*Name*	*KPI focus*	*Cell attribute*
Standard network systems (subsection 6.2.1)			
N/A	"Baseline (no SON)"	N/A	N/A
Default	"Default SCV settings"	N/A	N/A
Global objectives (subsubsection 6.2.2.1)			
Managed	"Performance"	User satisfaction	N/A
	"Robustness"	Handover success ratio	N/A
Local objectives (subsubsection 6.2.2.2)			
Managed	"Performance Urban,	User satisfaction	Urban
	Robustness Rural"	Handover success ratio	Rural
	"Performance Rural,	User satisfaction	Rural
	Robustness Urban"	Handover success ratio	Urban

OPEX to some extent, but at one point in time, the underlying network requires an update so that CAPEX cannot be avoided without harming the business model of the MNO. Yet, just reducing OPEX and CAPEX is not enough these days. With the ever-increasing complexity of a modern mobile network, an MNO also needs to run its system as efficiently as possible. For that, achievable KPI goals or targets need to be defined beforehand. A few general examples regarding such goals have already been given in chapter 1. Table 6.1 provides a couple of more precise cases. Along with a "Baseline" objective, where no SON functionality is active, one way is to let the SON functions run with the default (SCP) values. The next consequential step is to allow the MNO to focus on one KPI and let the PBSM system manage and set the right SCVs accordingly. Last but not least, the last rows of Table 6.1 define objectives that do not only focus on two KPIs but also on two distinct parts of the network. The reasoning behind this is as follows: The operator objectives cover a plethora of cases in an inhomogeneous system. A high throughput at noon has to be achievable in the city centre, but not necessarily on the motorway at the same time. Alternatively, a high cell density is required during the busy hour, but not at night times. With the given objectives and the availability of SON functions, the MNO shall steer the network in a way that the goals are further refined. This procedure requires a so-called SON policy repository that maps the objectives with the appropriate SCV sets. Table 6.2 gives an example for such a repository. The usage is simple: For a given cell class (i.e. a combination of cell attributes), and policy (i.e. the translation of (high-level) operator goals into a machine-readable language) the SCV sets can be looked up and deployed in the system. Please note that the numbers shown in Table 6.2 herein are arbitrary and exclusively serve as an illustration.

Table 6.2: Example for a SON policy repository containing every SCV set IDs for each SON function (compare Table A.1 to Table A.3 in the appendix) and each every class ID (see Table 4.1 in chapter 4)

Class ID	**LB SCV set ID**			**RO SCV set ID**			**TS SCV set ID**		
	Policy 1	...	*N*	*Policy 1*	...	*N*	*Policy 1*	...	*N*
1	4	...	9	13	...	2	22	...	5
2	2	...	17	3	...	9	4	...	1
⋮	⋮	⋱	⋮	⋮	⋱	⋮	⋮	⋱	⋮
M	18	...	6	9	...	15	2	...	9

6.2 Evaluation of SON Function Steering

As shown in Table 6.1, the impact of SON functions on the live network performance is explored in four consecutive steps. At first, a default parametrisation for each SON function is assumed in subsection 6.2.1. For more information on the actual SCVs, see [Lob+10] for LB (using the colour *orange* in the following figures, as it has been done in chapter 5), [Jan+10] for RO (using *yellow*) and [Kov+14] for TS (using *blue*), as well as Table 4.4. Here, each SON function is operating in a "stand-alone" manner, meaning that no other SON function is active at the same time. In a further stage, all functions run in parallel, again with a default parametrisation (using *red*). After that, the management functionality (see Figure 6.5 later on in subsection 6.2.2) is added and it is tried to steer the network towards more *performance* (i.e. a lower fraction of unsatisfied users, using *blue*) or towards *robustness* (i.e. higher HOSR, using *green* in Figure 6.6). In a final stage, the objectives are even further refined. The refinements are applied in a way that different objectives are given for the two possible cell locations – *urban* and *rural* cells. Figure 6.2 aims at clarifying the entire simulation and evaluation approach. The upper part summarises the SFPM creation, which has been done in chapter 5. The lower part shows the different evaluation stages of the four KPIs, which have been defined in section 2.3.

6.2.1 Default SCV Settings

The following two sections consider the default SCV settings, potentially provided by the vendor of the SON functions, to investigate the network performance. This allows a

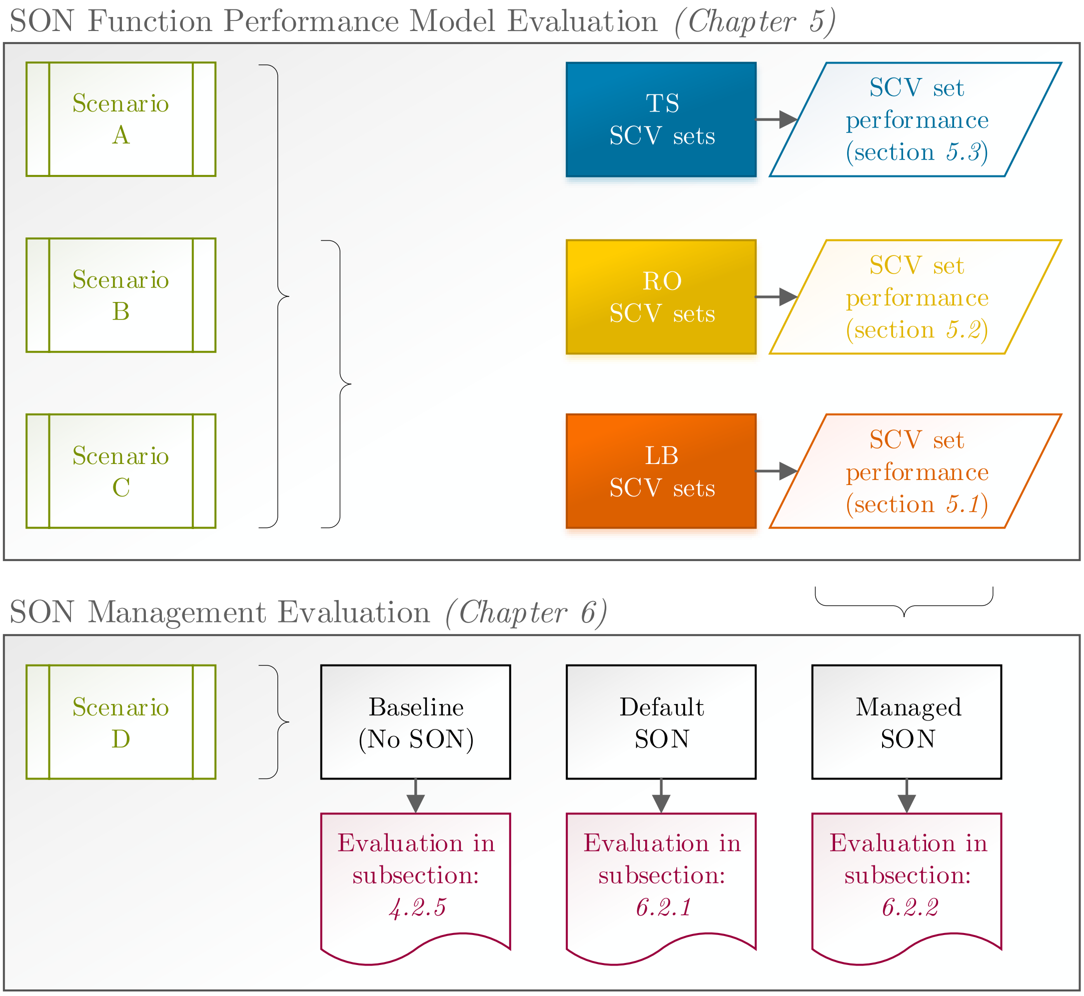


Figure 6.2: The SON function and SON management evaluation approach

greater insight into the capabilities of a SON-enabled system that is used as a reference to compare and evaluate different (management) approaches later on in this section.

6.2.1.1 Stand-alone SON functions

Figure 6.3 shows the results for the course of the whole simulation period of three hours for a stand-alone SON function operation. All four KPIs are comparable to the baseline scenario, meaning no SON function is active. Regarding the cell load (cf. Figure 6.3a), one observation is that the results vary for each SON function. This means that the (radio) parameter changes, executed by the three SON functions, influence the cell load performance. But it is not possible to evaluate whether the changes are good or bad because the variations are subtle and do not feature a clear impact on the overall performance. Please also note again, that the amount of total subscribers in the system is not fixed and thus the offered traffic is not stable. A more profound statement can be given by looking at the mean cell throughput (Figure 6.3b). Regarding the TS function, a partial improvement is often noticeable, i.e. the blue line is above the black line (baseline). As seen with the cell loads, the LB and RO functions only exhibit a minor impact on the cell throughput. The TS function improves the fraction of unsatisfied users, too, but the LB can also (sometimes) help to improve this KPI, see Figure 6.3c. This does not mean that the LB function is not capable of reducing the number of unsatisfied users. The abilities are often simply not given to do so in a proper manner. Where the TS is beneficial for both, the cell throughput and fraction of unsatisfied users, it has an adverse impact on the HOSR as shown in Figure 6.3d. Users connected to WiFi usually experience a bad HP. On the contrary, the RO function is clearly able to improve the HOSR, because the main objective lies on the HO optimisation.

These results are all expected and prove that the implementations of the SON function work as desired in the realistic network scenario. However, the performance gains are quite marginal and sometimes even counteracting. These results are also in line with the work of [Jan16, pp. 75], where an RO function was investigated in a realistic, but also in a hexagonal network layout. The latter showed remarkable performance gains, whereas the realistic network scenario did not do all the time.

6.2.1.2 Combinations of SON functions

Figure 6.4 shows the results if all three SON functions run in parallel. Please note that no (SON) coordination function is active that might prevent SON functions to execute (radio) parameter changes. As a reference, the results of the stand-alone operations are plotted in light colours. Now, a combined SON function operation also leads to differences in the cell load performance, see Figure 6.4a. Not only compared against the baseline scenario (no SON active, see black lines), but also with respect to the stand-alone operation of the three SON functions. This is a first indicator that the SON algorithms influence each other by changing *separate* (radio) configuration values in the network. Regarding the cell throughput, all SON functions together can improve the performance most of the time (see Figure 6.4b), even though not as sound as the single TS functions. Additionally, the combined operation can lead to very high values, but can also have a negative influence (see annotations in Figure 6.4b). The fraction of unsatisfied users (see Figure 6.4c) is more or less on the same level. Regarding the HOSR, one can observe that the performance at first degrades, mostly due to the LB and TS functions (see Figure 6.4d) which both have a severe impact on the HP

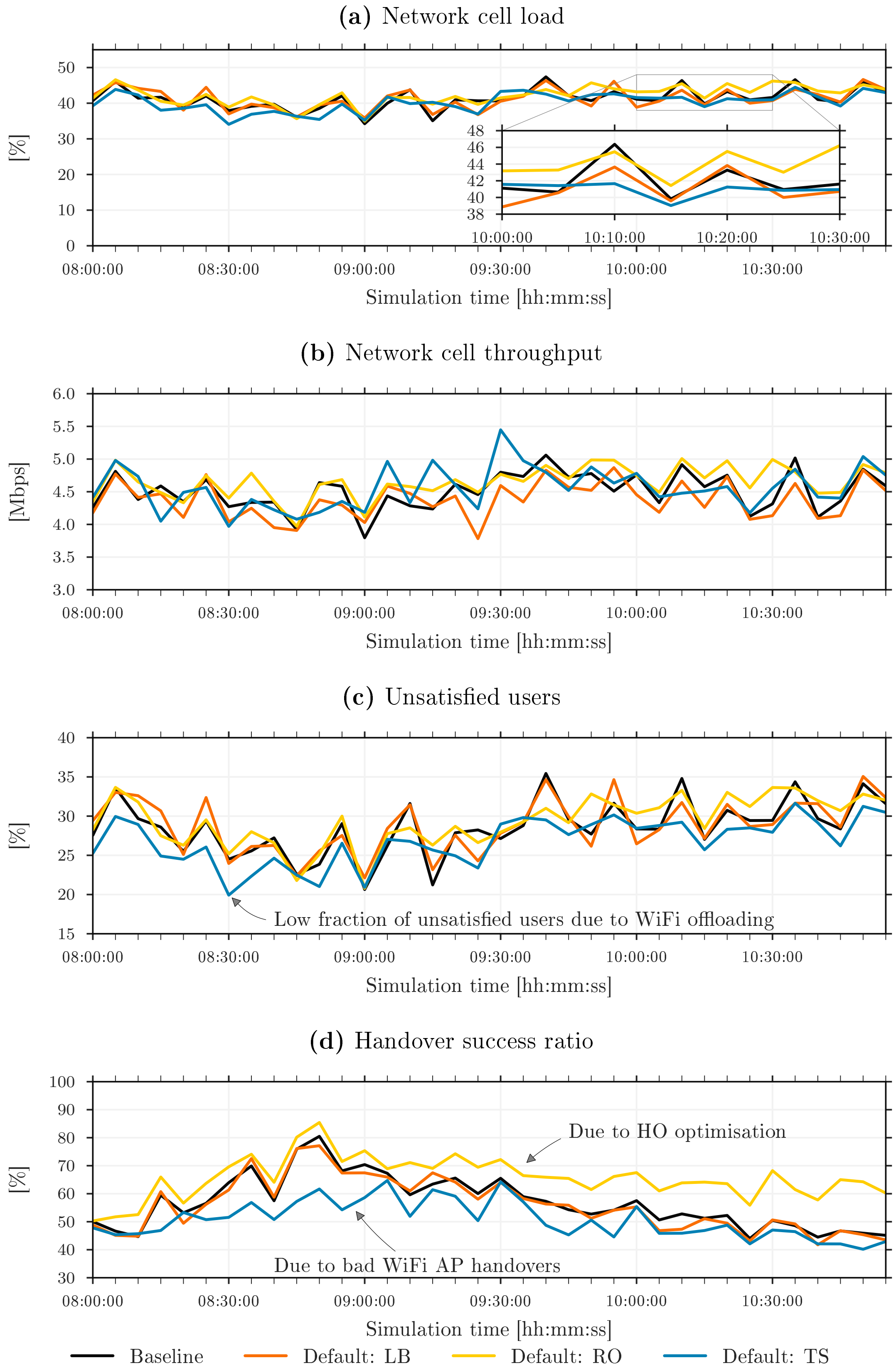


Figure 6.3: Stand-alone SON operations

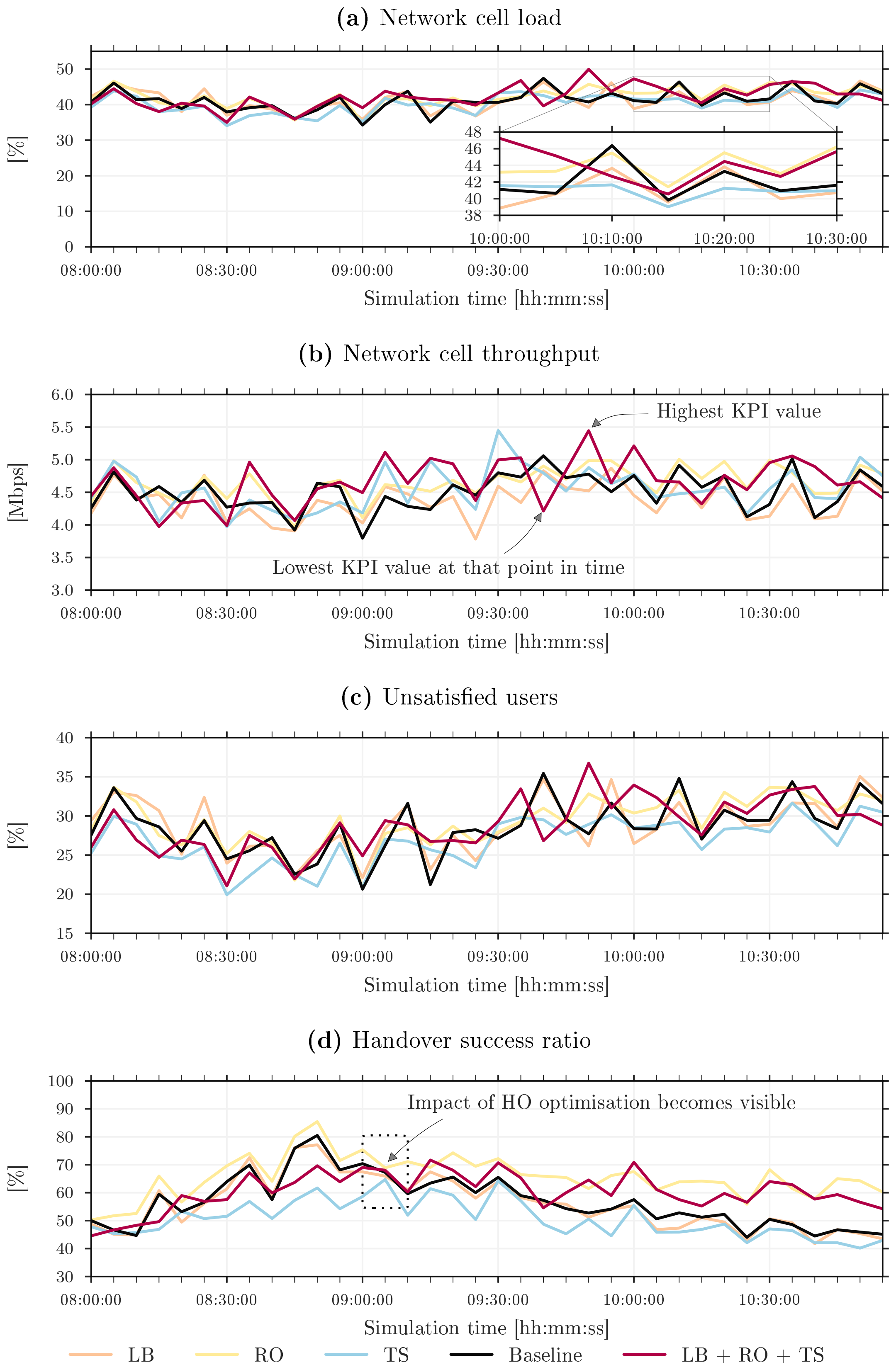


Figure 6.4: Combined SON operations

in general. However, later on, the changes of the RO function lead to a performance improvement (marked with a dashed rectangle in Figure 6.4d). This is due to the KPI collection phase of the RO function that usually takes time. Also, the RO algorithm parameter change frequency in the network compared to the other SON functions.

Two statements about a combined SON, compared to a stand-alone, operation can be made. Firstly, the KPI behaviour of the combined SON operation seems to follow particular SON functions, i.e. the RO function causes a greater HOSR performance and the TS functions tend to improve the fraction of unsatisfied users. This means that one or more SON algorithms are more or less dominating the outcome of the whole network performance. Secondly, KPI improvements, as well as degradations compared to a stand-alone and the baseline operation, can be seen. This indicates an actual need to select SON functions wisely and do not solely rely on (pre-defined) standard SCV settings provided by the vendors.

6.2.2 Managed SCV Settings

In the following, the SON management procedure given in Figure 6.5 is used. The SFPMs for each SON function are stored in repositories on the left. Table 6.2 already gave an example for such repositories. In the middle, one can see the "Mapper", which is a simplified version of a SOM. Additional information that the "Mapper" needs are the MNO objectives (see for example Table 6.1), shown as a white block, and the cell classification entity shown in grey (see also chapter 4 for further explanations). Finally, the outputs are respective SCV sets for each SON function and for all cells in the network that shall administer the operator objectives. The decisions of the "Mapper" are based on simple Event-Condition-Action (ECA) rules, as presented in [FLS14a], [FLS14b], and in Equation 6.1. ECA rules follow the event-condition architecture [DGG95]. An example in the domain of mobile network management could be the following: If a cell is classified as Class_4 (*event*) and the operator objective is to maximise the throughput (*condition*) then use, e.g., SCV set ID 1 for LB, ID 5 for RO and ID 3 for TS (*action*).

$$\text{IF } \textit{event} \text{ AND } \textit{condition} \text{ THEN } \textit{action} \tag{6.1}$$

As a reference, the baseline and the performance of the combined SON operation with the default SCV settings are shown in the following figures. The assumption is that an MNO uses all available and purchased SON functions, hence the combined operation.

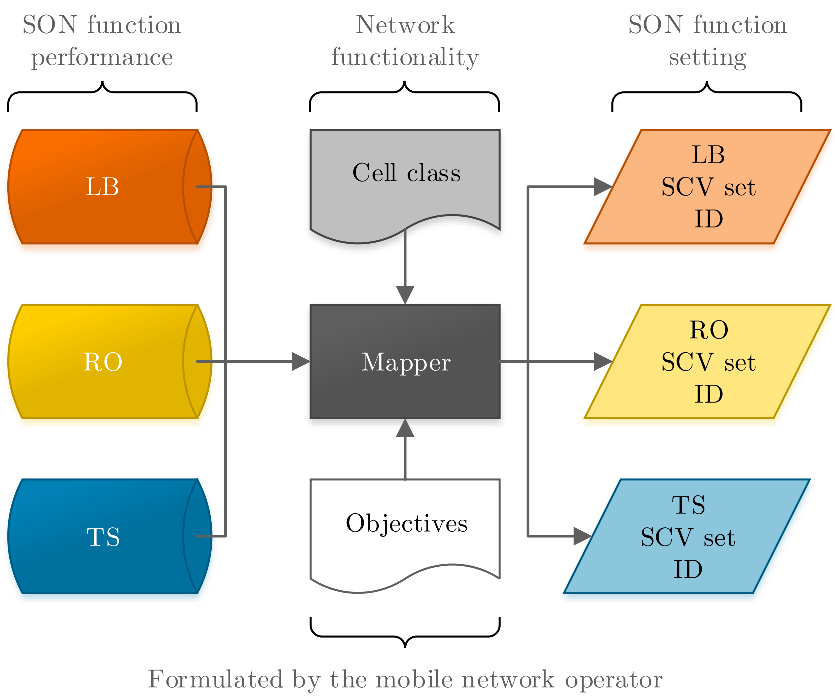


Figure 6.5: The mapping process: from cell class and operator objectives to enforced SCV set IDs in the network

6.2.2.1 Global Network Objectives

The results regarding the four KPIs with an enabled PBSM functionality are shown in Figure 6.6. The blue lines represent the objective *performance*, whereas the green line shall improve the *robustness* of the network. The objectives here are valid for all cells in the network. Meaning that, regardless of the cell context information, the SCVs for all three SON functions are set at either reducing the fraction of the unsatisfied users or at maximising the HOSR for all cells in the entire network.

Figure 6.6a presents the performance for the managed SON functions in respect of the first KPI, namely the cell load. Most of the time *performance* leads to lower cell load values. However, compared with previous results (see also Figure 6.3a and Figure 6.4a), the differences are only subtle here. Similar results are notable when considering the cell throughput values in Figure 6.6b. On the whole, the distinctions between both KPIs are hard to make for both objectives. In consequence, whether or not a PBSM system is beneficial cannot be answered, yet. Having a closer look at the fraction of unsatisfied users in the system in Figure 6.6c, one can see that the objective *performance* (blue line) indeed leads to the lowest values. Only with a small exception later on (around the 09:00:00 o'clock mark), when the baseline (black line) provides the lowest values. This is mainly due to the complex and changing data

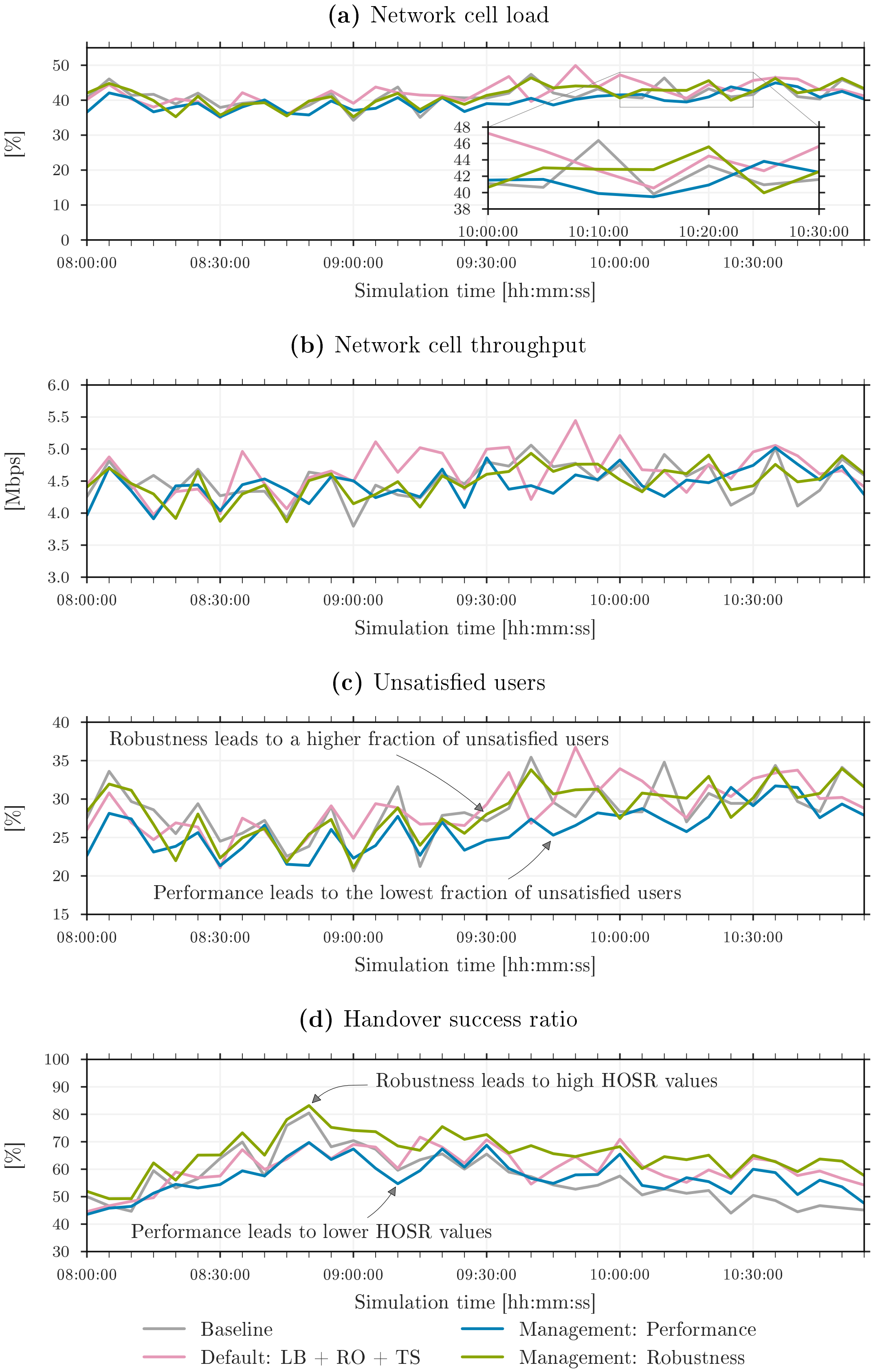


Figure 6.6: Managed SON operations

traffic conditions in the system. Even though SON functions constantly try to update the (radio) parameters, sometimes the changes lead to a performance degradation. However, this can still be seen as a desired outcome, since the SCVs are set at achieving just this KPI behaviour (i.e. reducing the fraction of unsatisfied users). The objective *robustness* results in a performance which is comparable to the default or baseline case. Regarding the HOSR (see Figure 6.6d), the objective *robustness* results in the highest values, which is as desired. Also, especially this objective, i.e. the SCVs which are set at improving the HP, outperforms all other settings.

It can be seen that by changing the SCV sets based on the current cell context attributes, SON functions can indeed steer the network performance in order to achieve dedicated MNO objectives. Apart from that, it is possible to outperform the default SON parametrisation with the managed SCV sets. With these, the SON functions are configured to improve one specific KPI. This explains that the impact on the cell load or throughput values is not as clear as for the fraction of unsatisfied users or the HOSRs.

6.2.2.2 Further Refined Objectives

Figure 6.7 and Figure 6.8 show the results if the objectives *robustness* and *performance* are not only valid for the whole network, but are further refined based on the (two) cell locations (cf. Table 6.1). This means, e.g, for all urban cells the objective is set at *performance* and for rural cells at *robustness* (using *green*) and the other way around (using *blue*). To focus on the refined simulations, only the two main KPIs (the fraction of unsatisfied users and the HOSR) are now shown for a) the entire network, b) all urban cells, and c) all cells in a rural location, respectively.

Regarding the first KPI, i.e. the faction of unsatisfied users, it can be seen that the objective refinement only works for one type of cell location. By considering just the rural cells (cf. Figure 6.7c), the refinement which focuses on the urban cells leads to the best performance (green line below the blue line). This is not the desired outcome since the other refinement should lead to a smaller fraction of unsatisfied users (ideally: green line *above* the blue line). Overall, the performance changes are not as profound, compared to the global objectives shown in Figure 6.6c. This is since not all SON functions are active in the entire cellular network. For example, the TS function is only present in the urban part of the scenario – where WiFi APs can be found. This, of course, also limits the ability to improve the fraction of unsatisfied users in other parts of the system, because only the LB and RO are active here (also compare the results of chapter 5). Following this point, the objective for urban cells could be executed. The

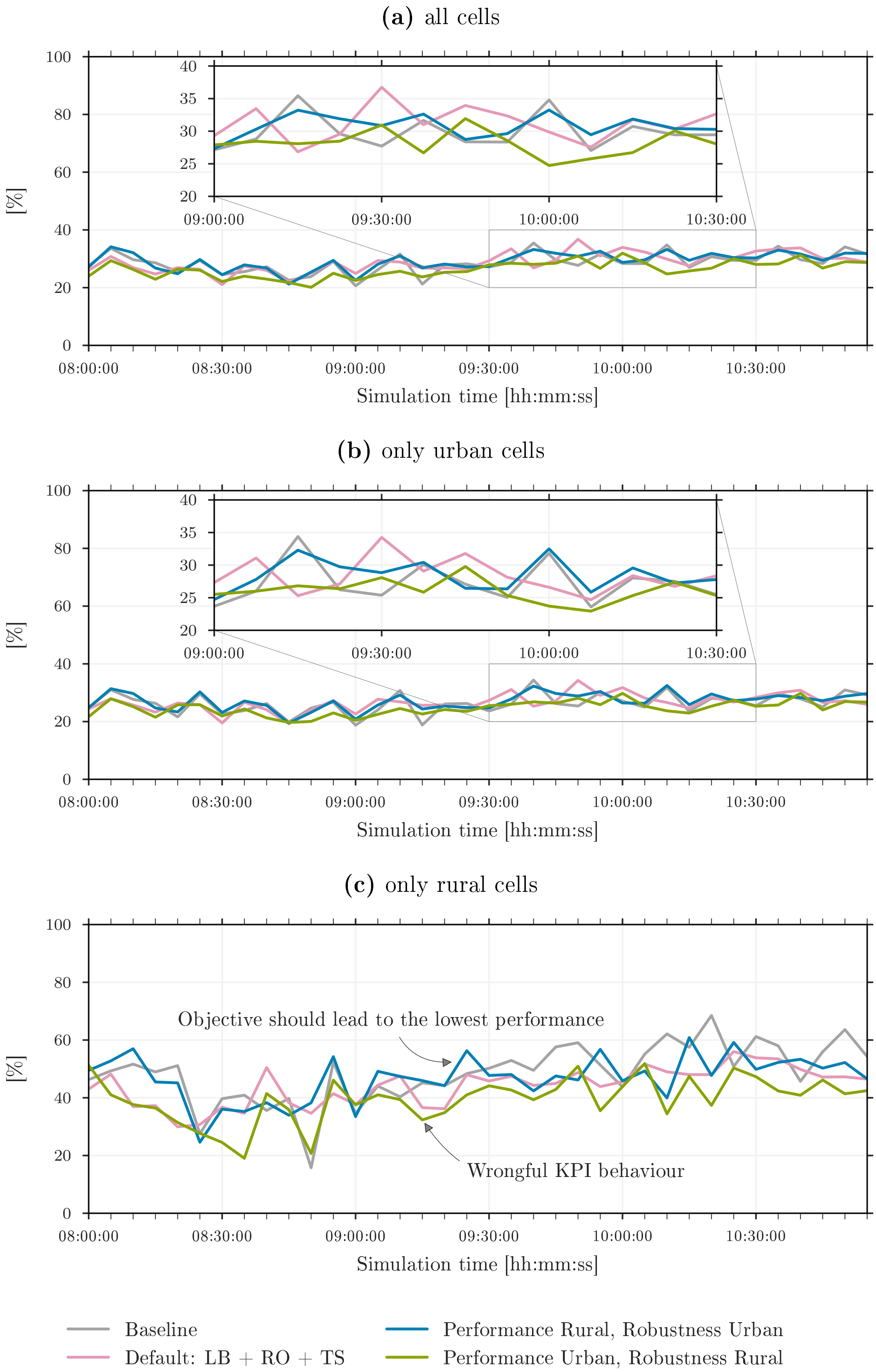


Figure 6.7: Managed SON operations (refinement): *unsatisfied users*

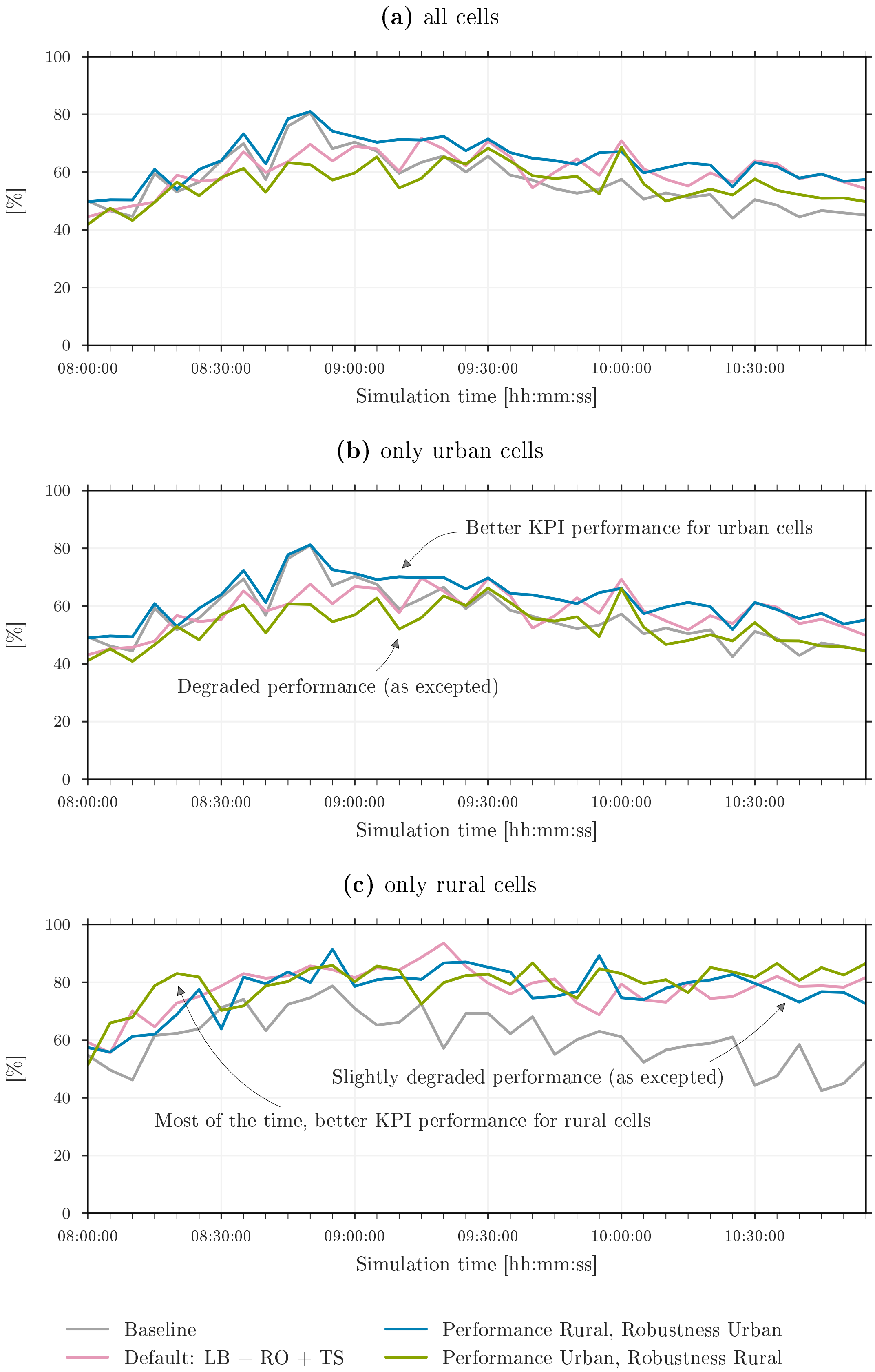


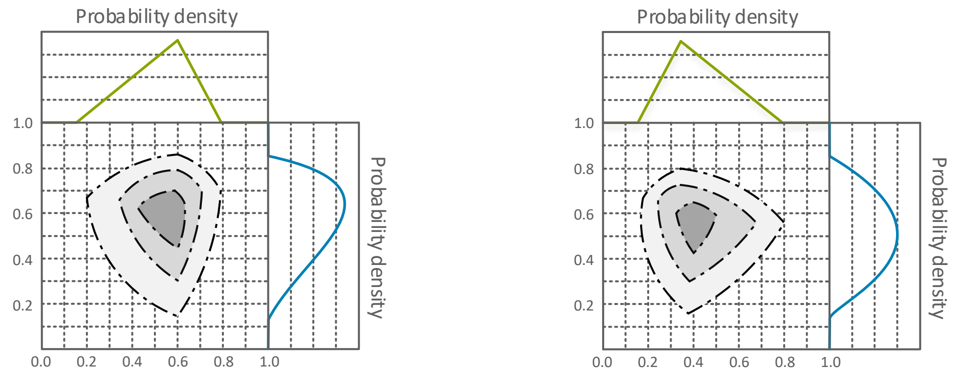
Figure 6.8: Managed SON operations (refinement): *handover success ratio*

other main KPI, i.e. the HOSR, features a better performance and shows the ability to steer the network towards dedicated directions. Here the SCV settings that are supposed to improve the HP in urban cells feature a better performance than the other settings (cf. Figure 6.8b, blue line above green line). Vice versa, considering only the rural cells, the opposite SCV settings show a better HOSR performance (cf. Figure 6.8c, green line mostly above blue line). A better performance is mainly observable later on when the impact of the RO function becomes noticeable. This slothful behaviour of the RO algorithm could be observed before when considering the SON functions in a stand-alone operation (see Figure 6.3d), because the RO function needs time to collect and evaluate HO measurements. Such statistics are built up over the course of the simulation time. Worth mentioning is also the fact that the managed SON functions can outperform the baseline (i.e. no SON functions) as well as the default SCV settings for both KPIs and the two cell location types. In addition, all results with an involvement of SON, so also the default (SON) parametrisations (*"Default: LB + RO + TS"*), lead to a considerable enhancement of the HOSR in rural cells.

The results about the further refined MNO objectives are not as clear as the global KPI target formulations (see Figure 6.6). On the one hand, the refinements regarding the HOSR are implementable. On the other hand, the second major KPI (the fraction of unsatisfied users) leads to a (partial) wrongfully enforced performance in the network. In conclusion, the MNO still has to be careful when operating and managing a SON enabled mobile system. Therefore, the following section now further investigates the interdependencies of the three SON functions to improve future SON management decisions.

6.3 Evaluation of SON Function Combinations

A remaining question that this work needs to answer – to finally pave the way towards a profound SON management – is how multiple SON functions *behave* when running in parallel. The approach throughout this thesis (e.g. chapter 5) was to derive the impact of SON functions on KPIs by simulating a *stand-alone* SON function operation. The assumption is that vendors have to provide necessary information, such as the SFPMs, by using simulations in a similar way. However, an MNO might have purchased many SON functions and is keen on using them all in its network in parallel. So the (SON) management system needs to *predict* the impact on the KPIs, if all SON functions are active and might influence each other. The author of [Fre16] presented a method to do so by combining the observed KPI Probability Density Functions (PDFs), derived from each SON function individually, into one single PDF. Figure 6.9 depicts this presentation of the problem by showing exemplary two-dimensional KPI-PDFs (shown in green and blue, respectively): for a system without SON functions active (see Figure 6.9a) and a SON-enabled network (see Figure 6.9b). With SON, the PDFs change and, thus, the system also behaves differently. Yet, [Fre16, pp. 112] did only a *theoretical* evaluation. Consequently, the following sections investigate the effects of a combined SON operation on the actual network performance by *simulating* the large-scale reference scenario (as defined in subsection 4.2.5) with different SON combinations. This ultimately answers the question if a SON function, that is optimising one KPI, is still affecting this KPI in the same way when running in combination with other SON functions. Also, the SON management system can make use of the *predicted* KPI behaviour and improve the management of SCVs accordingly.



(a) Baseline, e.g. no SON active **(b)** Impact of SON executions

Figure 6.9: Exemplary context-dependent, probabilistic effects of configuration changes resulting from SON actions on KPIs based on [Fre16, pp. 110]

Consequently, subsection 6.3.1 presents the simulation results about the impact of different SON combinations on the entire network, as well as on the defined cell classes (cf. Table 4.1). These combinations include: the three SON functions in a stand-alone operation (*"LB"*, *"RO"* and *"TS"*, i.e. no other SON function is active, using the colour *brown*), combinations of two SON functions running in parallel (*"LB + RO"*, *"LB + TS"* and *"RO + TS"*, using *green*) and all three SON functions together (*"LB + RO + TS"*, using *blue*). Again, no SON coordination entity is active that prevents SON functions from possible undesired (radio) parameter changes. Additionally, a reference scenario with no active SON functions at all is simulated ("Baseline", using *purple*). After that, subsection 6.3.2 further investigates a probabilistic combination and the actual effect of combined SON functions to enable a "coordinated" SON operation, which will be presented in subsection 6.3.3.

6.3.1 Impact of SON Function Combinations on the KPI Behaviour

Figure 6.10 shows the load distributions, for each RAT separately, and for each possible SON function combination. Noticeable are the rather low load values for the WiFi APs. This is because of only a few users, if any, connect to the APs and, thus, do not compete with many users about the available resources. Furthermore, it can be seen that each of the SON combinations alters the cell load performance. However, the changes are more subtle compared to the following KPI, the HOSR.

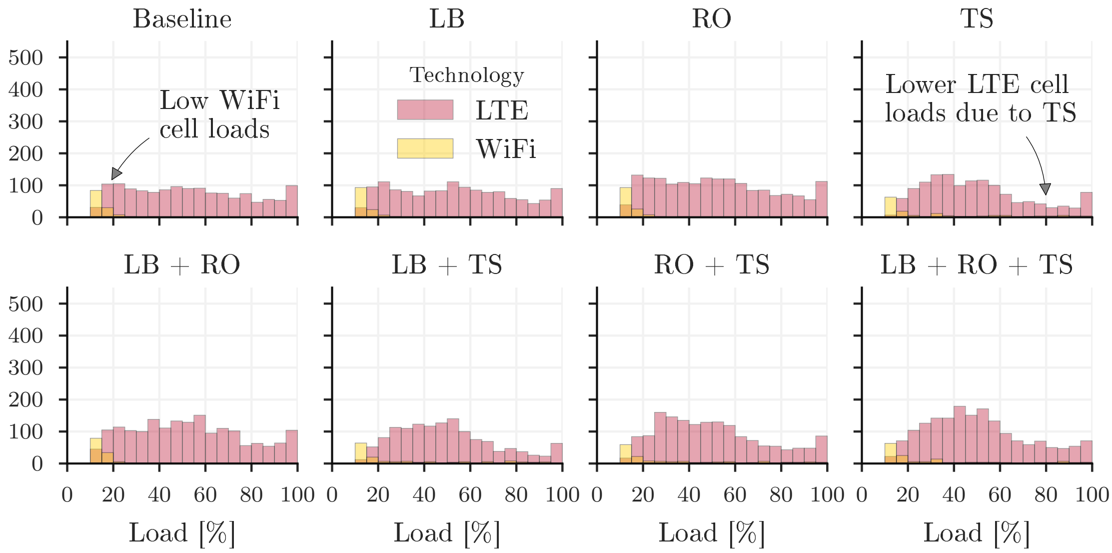


Figure 6.10: KPI distributions for different SON function combinations: *network cell load*

The HOSRs for the eight combinations are shown in Figure 6.11. Similar to the rather low WiFi load values, the HOSR is also bad for WiFi APs. This effect was notable many times throughout this thesis. Due to the small cell sizes and rapid RSS variations the HOs often fail. Higher HOSRs are achievable by adding the RO function. This behaviour is, of course, as desired because RO is deemed to optimise the HP. On the contrary, the SON functions that tackle load or traffic problems in the system, i.e. LB and TS, often lead to a degraded HOSR performance. This is also as expected because the load and traffic distributions are usually coupled with deteriorated HO executions.

Now, to get an even finer and detailed look on the performance, Figure 6.12 and Figure 6.13 show the two-dimensional KDE plots (similar to the example of Figure 6.9) for the whole network (first row), and for the eight cell classes defined in Table 4.1.

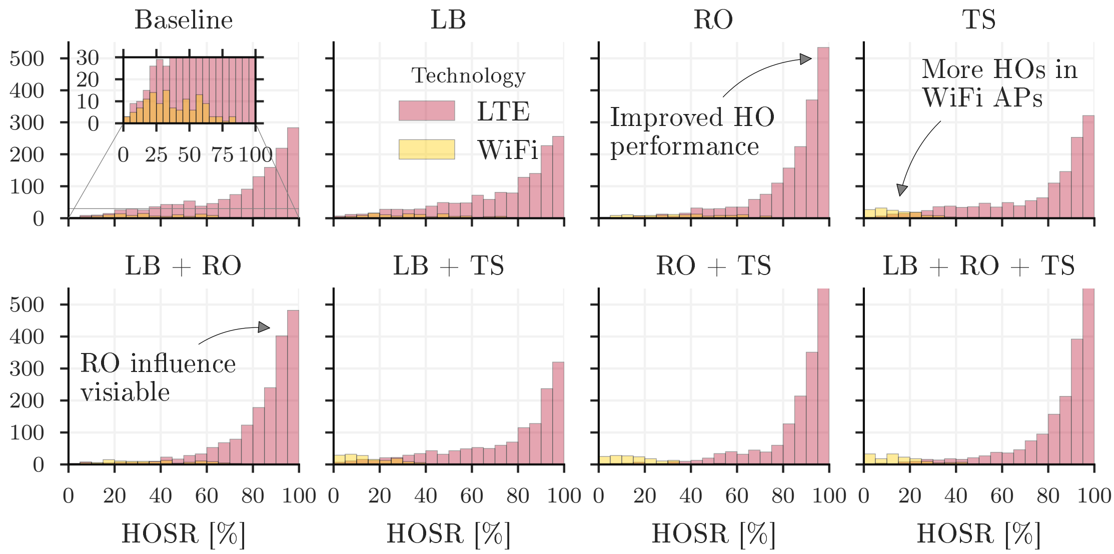


Figure 6.11: KPI distributions for different SON function combinations: *network handover success ratio*

With the KDE figures (using a Gaussian kernel function), both KPI distributions can easily be combined, observed, and evaluated whether dedicated SON functions lead to a desired performance changes in the system or not.

On a first glance at the different combinations, one can see that the KPI behaviour differs – not only for the entire network (i.e. all cells in the scenario, top row of Figure 6.12 and Figure 6.13), but also regarding the different cell classes. This can be further analysed by, e.g., having a closer look at the WiFi APs, i.e. class ID 1 and 2. Naturally, the (LTE/WiFi) TS function has the greatest impact on these two classes, which can also be seen here. The influence of LB and RO in a stand-alone operation (see 2^{nd} and 3^{rd} column of Figure 6.12, and especially “1a” and “1b”) is only subtle. After adding the TS function to one of the other SON functions, a shift towards lower HOSR and higher cell load values is noticeable for both classes. This shift is due to the offloading from LTE cells towards WiFi APs, which offer more capacity in this scenario. However, this comes with the disadvantage of a bad HP, due to smaller cell sizes and greater RSS variations of the WiFi APs. Having a look at the RO function, an improvement of the HOSR is noticeable in almost all cell classes (i.e. a shift towards higher values in the KDE plots, see “2a” and “2b”). Except for class ID 1 and 2, but as mentioned, only WiFi APs are in these classes. Hence, this LTE SON function can barely influence these cells. Class ID 8 (“2c”) also shows a worsened HOSR performance; highly loaded, rural cells featuring high-speed users, indicate bad interference conditions and fast RSS changes due to the high velocity of the users. This

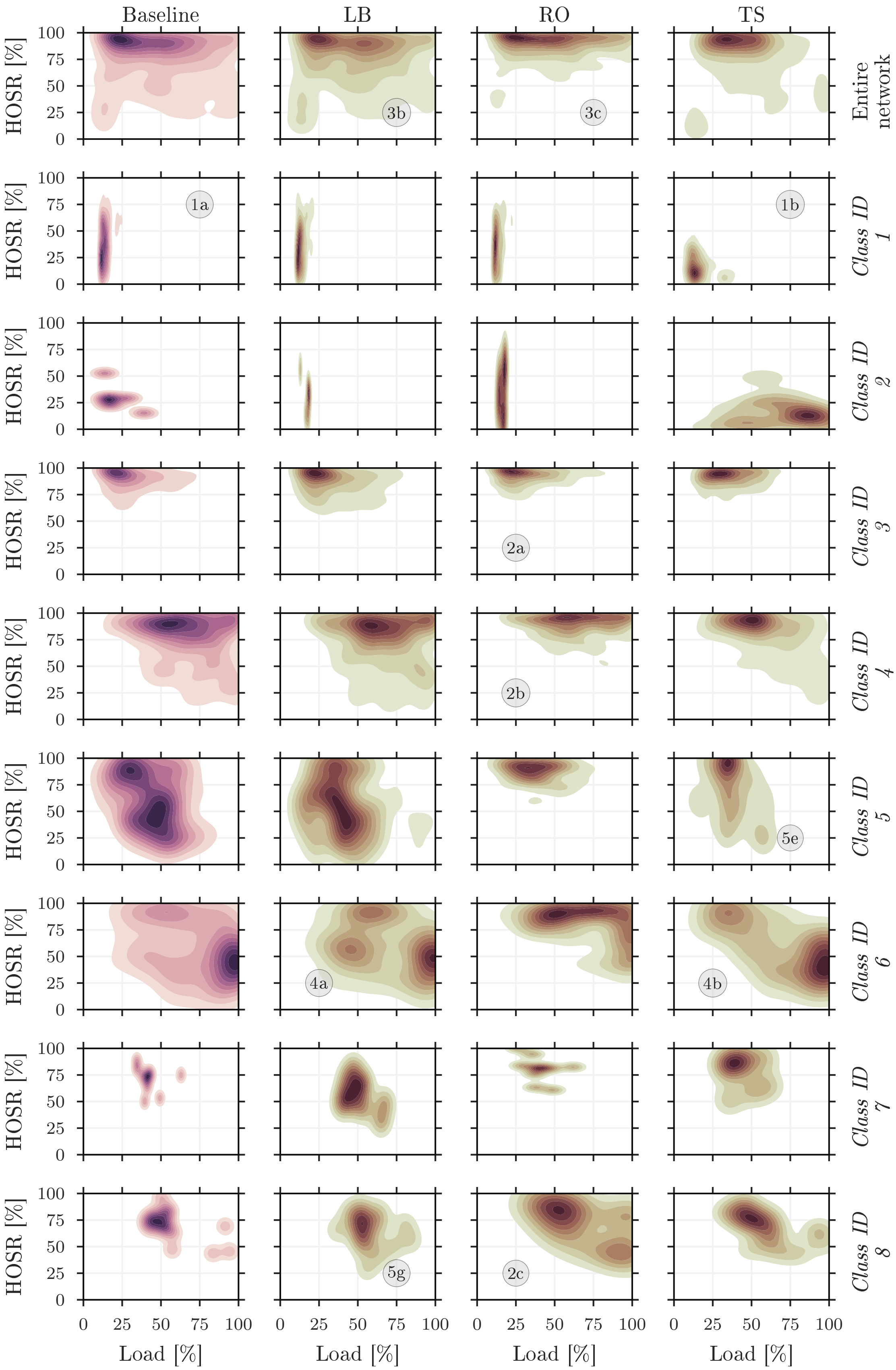


Figure 6.12: Impact of SON on different cell classes: *Baseline (purple) and stand-alone operation of a single SON function (brown)*

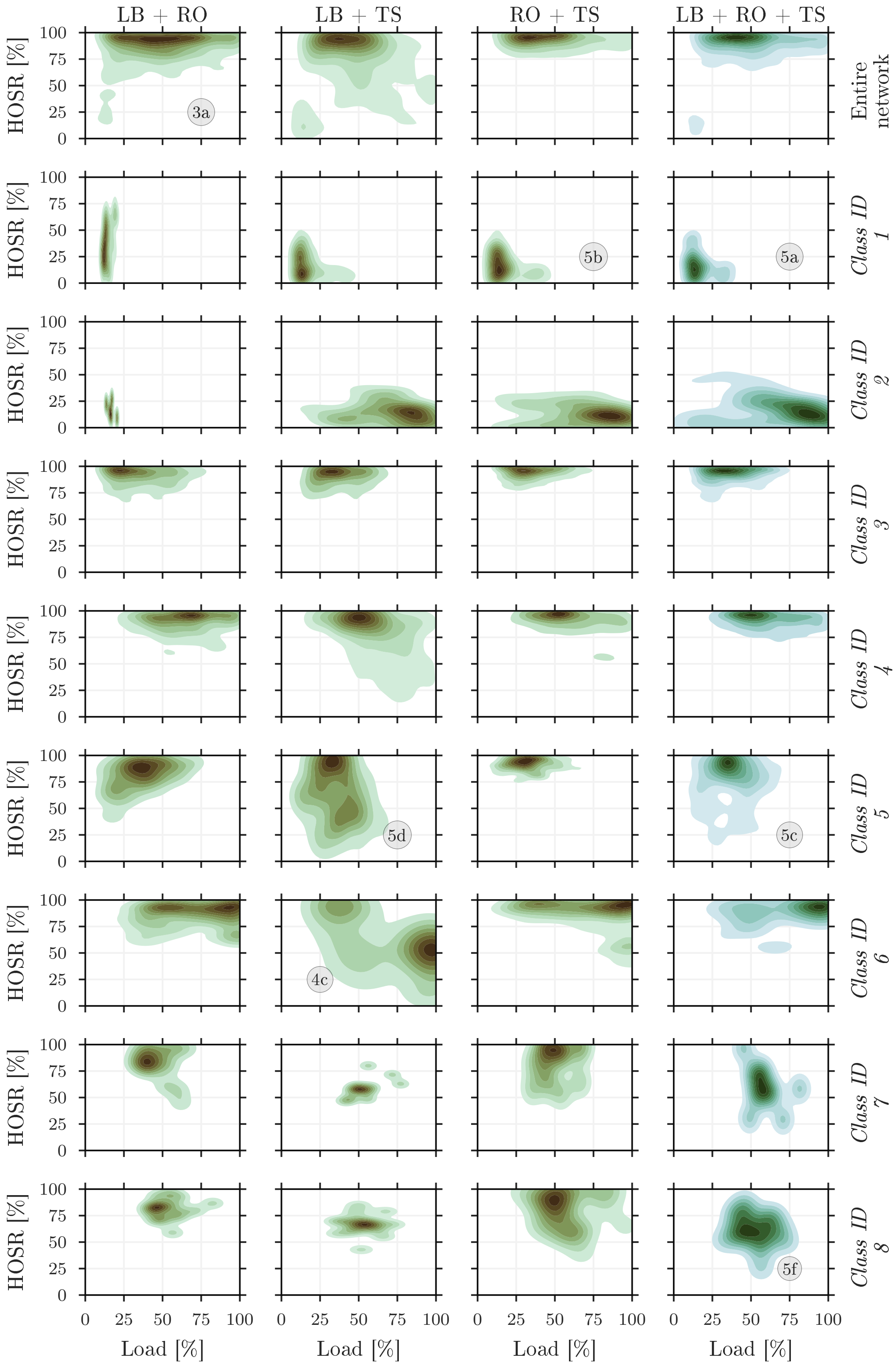


Figure 6.13: Impact of SON on different cell classes: *Two SON functions running in parallel (green) and all three combinations together (blue)*

might be a situation where the RO function is having difficulties finding appropriate HO settings. Another result is that with a combination of two SON functions, the negative effect of one function can somehow be compensated. Considering, for instance, the LB algorithm: by shifting users to less loaded cells the HP often deteriorates, due to degraded RSS conditions. Now, by adding the RO function this undesired behaviour is mitigated – see first row of *"LB"* and *"RO"* in Figure 6.12, as well as *"LB + RO"* in Figure 6.13 ("3a", "3b" and "3c"). LB and TS showcase another effect of SON function combinations. Both functions influence the cell load values in the network. The LB function shifts users within LTE by changing CIO values, whereas TS steers the traffic between LTE and WiFi by adjusting the (WiFi) RSS thresholds. This fact is also visible by inspecting the different cell classes and comparing the KDE plots to each other. See for example class ID 6 for the results of *"LB"* and *"TS"* in Figure 6.12 and the combinations of both (*"LB + TS"*) in Figure 6.13, i.e. "4a", "4b" and "4c".

Lastly, by combining all SON functions (last column in Figure 6.13), it can be seen that the influence of all SON functions is noticeable in the KPI behaviour. The performance in each row (i.e. each class) can be compared with a previous SON combination (i.e. another column) – even though, the SON combination differs. For example, the *"LB + RO + TS"* performance of class ID 1 can be compared to the results of *"RO + TS"* of class ID 1 ("5a" and "5b"), the *"LB + RO + TS"* performance of class ID 5 is comparable to *"TS"* or *"LB + TS"* ("5c", "5d" and "5e"), the *"LB + RO + TS"* performance of class ID 8 is comparable to "LB" ("5f" and "5g"), and so on. This also leads to the conclusion that the different environments in a large-scale heterogeneous network have a profound impact on the SON performance. These behaviours will be further evaluated and validated in the next section by focusing on a probabilistic analysis.

6.3.2 Probabilistic Combination of Different SON Functions

After evaluating various SON combinations, the question remains if and how multiple SON functions (which are operating "stand-alone") can easily be combined so that the resulting KPI influence is predictable and usable for future (self-organising) network management decisions. This is of high importance when it comes to assigning appropriate SON function combinations, i.e. to guarantee the predefined KPI targets and to prevent an undesired network behaviour. As Christoph Frenzel defined in his dissertation thesis, the combined KPI effect of SON functions can be expressed by Equation 6.2 [Fre16, pp. 113]:

$$\Pr(V_k \in W_k) = \sum_{s \in S} \gamma_s \cdot \Pr(V_{k,s} \in W_k) = \sum_{s \in S} \gamma_s \cdot \int_W f_{k,s}(\nu)\,\mathrm{d}\nu \tag{6.2}$$

V_k represents the random variable which describes a KPI k in its corresponding value range W_k. Furthermore, $f_{k,s}$ is the actual KPI effect for k of a SON function $s \in S$. Finally, γ_s defines a probability how a SON function dominates a certain KPI behaviour. In general, γ_s can be set at $1/|S|$, which means that each SON function "dominates" with equal probability. This γ_s now is of interest to combine SON functions rightfully.

6.3.2.1 The Kolmogorov-Smirnov Test

In order to check and derive the dominating probability γ_s for each SON function, Kolmogorov-Smirnov Test (KS-Test) is usable [CF09, pp. 80]. With the KS-Test it is possible to test two continuous, one-dimensional probability distributions against equality. The approach is relatively easy and as follows: the null hypothesis H_0 is that $F_n(x)$ equals $F_m(x)$ (see Equation 6.3).

$$H_0 : F_n(x) = F_m(x) \tag{6.3}$$

Now, the so-called Kolmogorov-Smirnov statistic $D_{n,m}$ is defined by the supremum (sup) of the set of distances, as shown with Equation 6.4:

$$D_{n,m} = \|F_n - F_m\| = \sup_x |F_n(x) - F_m(x)| \tag{6.4}$$

The null hypothesis gets rejected at a specified level α if $D_{n,m}$ satisfies the inequation of Equation 6.5:

$$D_{n,m} > c(\alpha)\sqrt{\frac{n+m}{nm}} \tag{6.5}$$

Where n and m are the sample sizes of $F_n(x)$ and $F_m(x)$, respectively. The literature provide potential values for $c(\alpha)$ or one can calculate the $c(\alpha)$ based on Equation 6.6.

$$c(\alpha) = \sqrt{-\frac{1}{2}\ln\left(\frac{\alpha}{2}\right)} \tag{6.6}$$

Lastly, Figure 6.14 illustrates the KS-Test with two exemplary cumulative distribution functions. Furthermore, the $D_{n,m}$ statistics can be transformed into a

P(robability)-value, which enables a convenient setting at a significance level. This value basically indicates the probability to obtain a sample result if H_0 is true. In other words, lower values indicate that it is more likely to reject H_0. So, if the P-value is below the significance level – here it will be set at 0.05 (i.e. 5 %) – one can reject the null hypothesis and, hence, the two distributions can be seen as dissimilar.

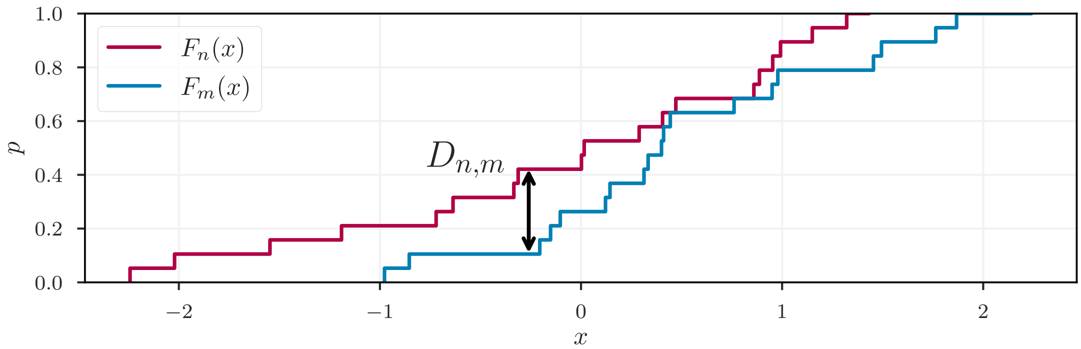


Figure 6.14: Principal of the KS-Test

6.3.2.2 Evaluating Multiple SON Functions

The calculated KS-Test results for the two KPIs from Figure 6.10 (using blue) and Figure 6.11 (using green) are shown as P-values in Figure 6.15 and Figure 6.16. The two figures show 16 plots in total. Each time one specific SON combination is the distribution to check against all others. In other words, one combination is $F_n(x)$ (and hence the reference) and the remaining ones are $F_m(x)$. $F_n(x)$ is also shown in light colours, which enables a quick identification. Additionally, the P-Values for the reference are all 1 (i.e. 100 %), because the distributions are the same. Also note that Figure 6.15 focuses on the overall network performance, whereas Figure 6.16 provides a detailed view on all eight cell classes if the baseline scenario is taken as reference.

In the first plot of Figure 6.15a, all SON functions (see x-axis) are compared to the baseline scenario with no active SON functionality. The three stand-alone SON functions reveal mixed characteristics: An LB-enabled system leads to almost no considerable changes in terms of the two KPIs, which is also emphasised by the high P-values. This finding is in line with all previous simulation results that have shown the limited abilities of the LB algorithm in this (realistic) scenario setup. The RO function, on the other hand, can result in a totally different KPI behaviour (hence the low P-values). Here, the SON actions (i.e. changing the HO operation point) lead to distinct KPI distributions, which is also comprehensible by looking again at the first

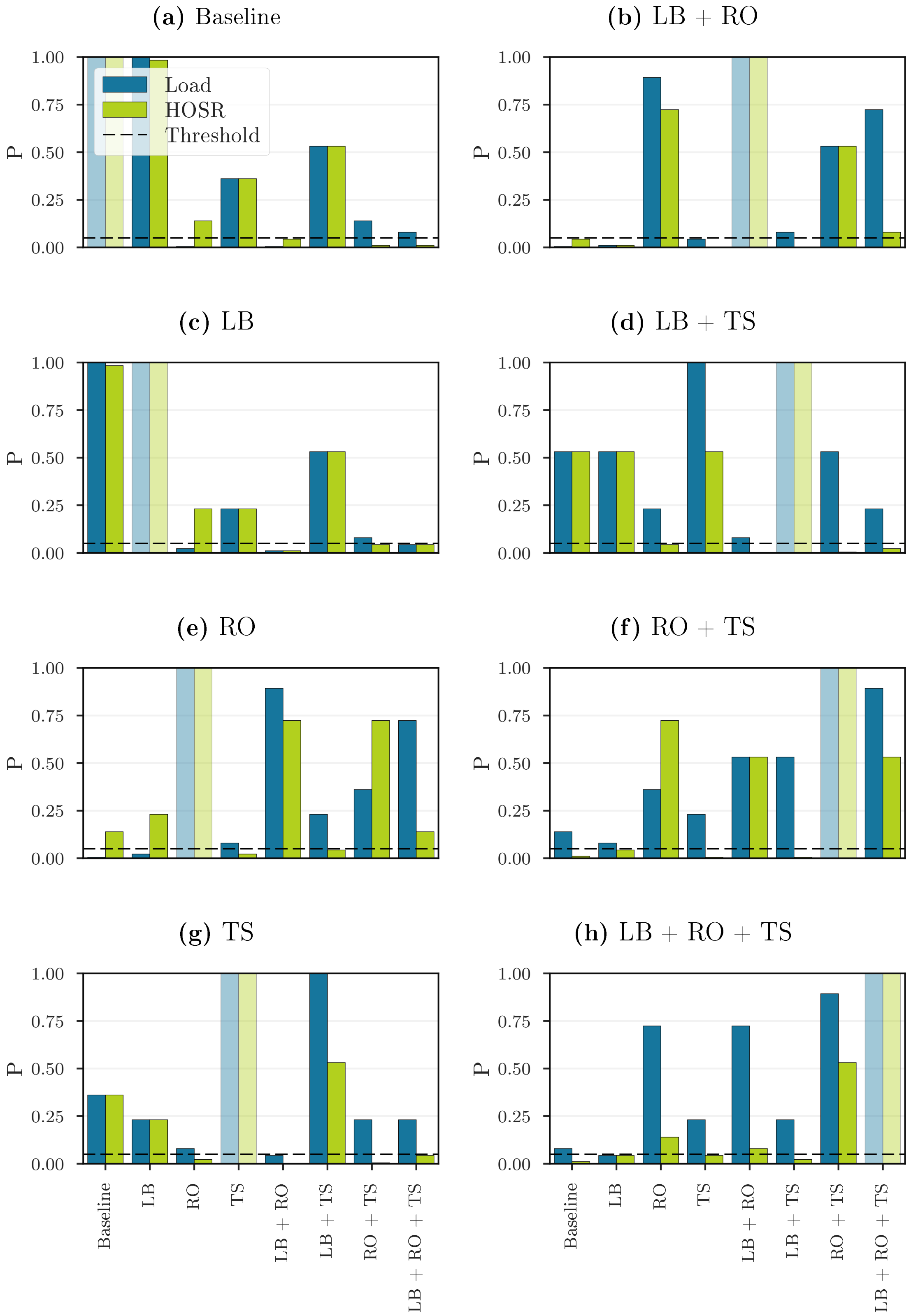


Figure 6.15: P-values for every *SON combination*, compared against each SON combination (the light colours indicate the reference, i.e. F_n, when using the KS-Test)

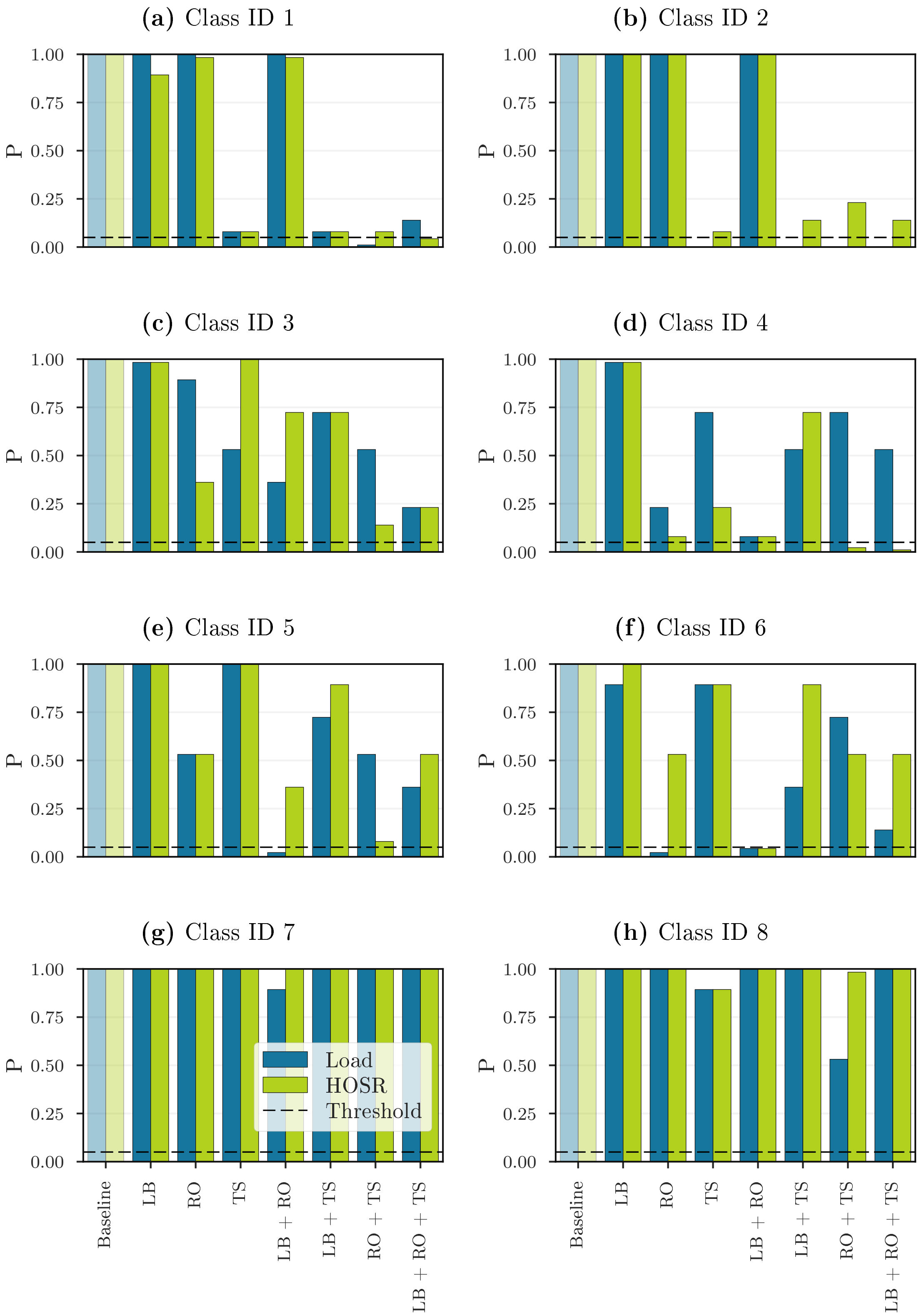


Figure 6.16: P-values for every *cell class*, compared against each SON combination (the reference, i.e. F_n, when using the KS-Test, is always the baseline scenario here)

row of Figure 6.12. The TS function (which is only available in the inner city of the scenario) lies in between the other two SON functions but is still above the significant level of 0.05. The following three plots on the left of Figure 6.15 are all well suited to analyse the combination of SON functions. For instance, by using the performance of the LB function as reference, shown in Figure 6.15c, one can compare the P-values of the remaining SON functions. The comparison reveals that the load behaviour for LB and RO is dissimilar, whereas LB and TS lead to a related KPI behaviour. This is understandable since both algorithms tackle similar (load) optimisation tasks. With Figure 6.16 one can observe which SON function has a greater influence on the eight cell classes. For instance, the TS function feature greater influence on cell class 1 and 2. But also on other classes which do not feature WiFi APs at all. These results have to be taken into consideration when combining SON functions as the following paragraph will show.

6.3.2.3 Combining Multiple SON Functions

Eventually, with the necessary build-up, i.e. the analysis on the impact of SON combinations in subsection 6.3.1 and the just mentioned KS-Tests, the dominating probability introduced ($1/|S|$) can be applied to simulations. Figure 6.17 presents the two-dimensional KDE plots for three combinations when using two SON functions. The first two plots (from top to bottom, using the colour *brown*) show the KPI distributions for the entire network if only one SON function is active (note that these are the same results as already shown in the first row of Figure 6.12). The next two plots (using *purple*) present a *theoretical* combination of the two previous SON functions based on Equation 6.2. This means that the results from the plots of the stand-alone operation with equal probability (or weight) are taken and overlaid to *predict* the resulting KPI performance. As the plots also highlight, different dominating probabilities are assumed in both cases. At first, γ_s is set at $1/|S| = 1/2$ – like it was done in [Fre16, p. 113]. After that, the probabilities (γ_s) got adjusted based on the outcome of the previous analysis as shown in the fourth plot of Figure 6.17a, Figure 6.17b and Figure 6.17c. The last plot (the fifth plot going from top to bottom using *green*) shows the actual simulated KPI distribution for the entire network when two SON functions run in parallel (again same plots as shown in the first row of Figure 6.13).

As the results state, the broader direction concerning KPI performance can be captured by the theoretical overlay of the two functions – even if an equal probability γ_s is assumed. This is particularly the case when considering the combination of TS and LB (cf. Figure 6.17c). These two function tackle one distinct problem; LB is trying

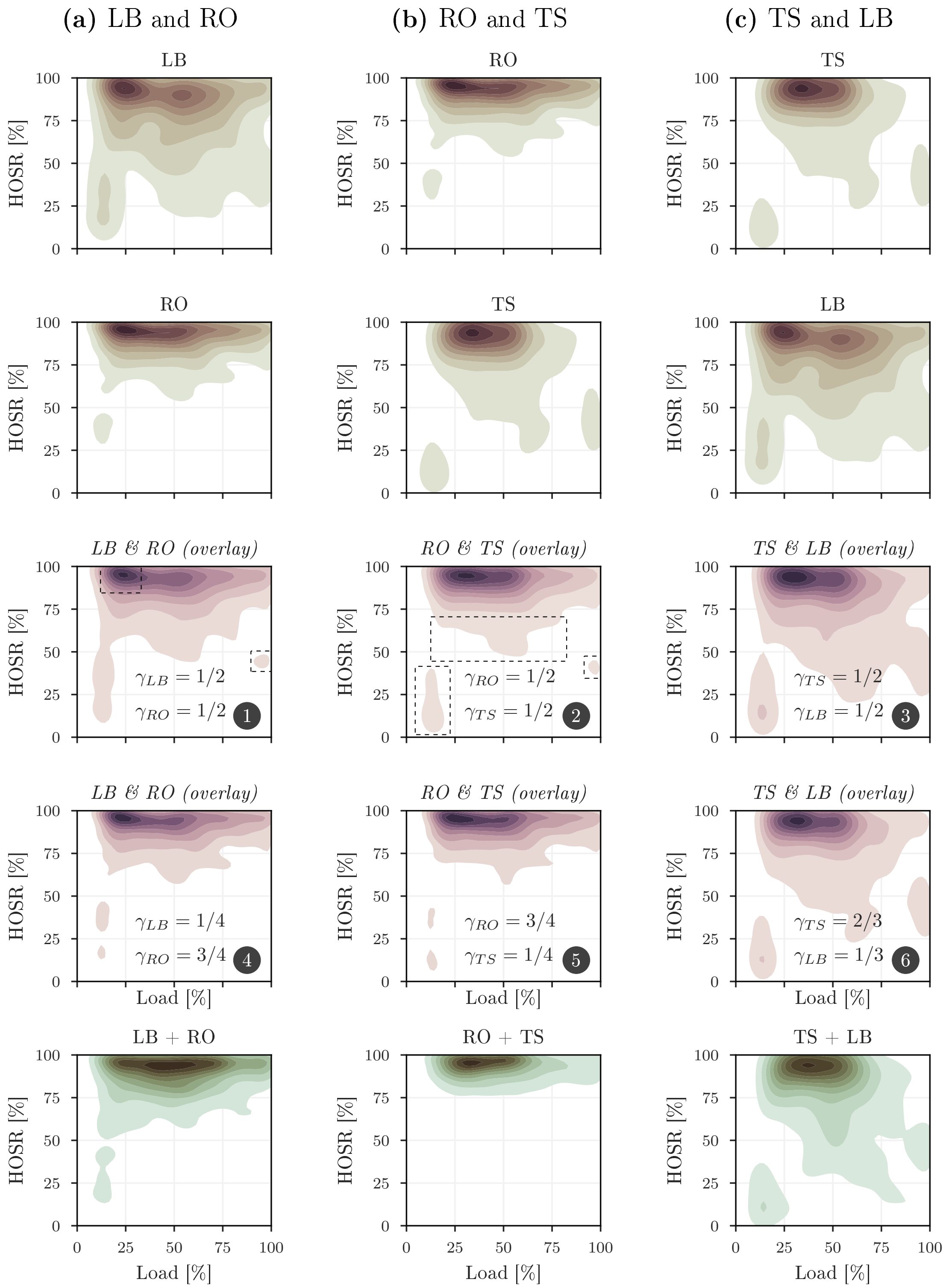


Figure 6.17: Effect of different SON function combinations on the entire network: *Stand-alone operation (plot 1 and 2 using brown), theoretical overlay with an equal and with an adjusted dominating probability (γ_s) (plot 3 and 4 in purple) and the actual performance (plot 5 shown in green), all from top to bottom, respectively*

to balance the load in the system, and TS is lowering the cell loads of a dedicated RAT. Each load affecting SON functions in combination with the RO function tend to produce a slight mismatch in terms of *theoretical* and *actual* KPI performance (emphasised with dashed rectangles in the third row of Figure 6.17a (see ❶) and Figure 6.17b (see ❷)). RO optimises the HOSR – a KPI that is negatively affected by the two remaining, load-optimising SON functions (see for example Figure 6.11 in subsection 6.3.1). With that, the bad HOSR performance provoked by the LB or TS SON functions are compensable to some extent. Furthermore, this coherence has also been shown with Figure 6.15 and Figure 6.16. Now, with adjusted probabilities γ_s (see ❹, ❺, and ❻), the results come closer towards the actually achieved distributions in the system. This is another sign that an MNO needs to be careful when combining and, hence, managing SON functions that tackle different optimisation goals in the network. Also, the system needs time to update available information regularly to guarantee a sophisticated (SON) operation. Like the detailed evaluation of subsection 6.3.1 also clarified, this cannot happen by a network-wide assessment only. It has to go down on cell class level or preferably even by incorporating individual base stations.

6.3.3 Improved SON Management Decisions

Finally, the outcome of the previous sections is now used to execute the further refined SON management decisions once again (cf. section 6.2), but this time by incorporating the finding and applying a simplified SON "coordinating" functionality. This approach selects the appropriated SON function combinations based on the results of Figure 6.12, Figure 6.13, and the dominating probabilities of subsection 6.3.2. Furthermore, the information gathered in chapter 5 is incorporated, too. For instance, the LB function is only active in situations during the busy hour of the cells. Please note that apart from the measures just mentioned, no advanced SON coordination methods (as in [Iac+15] or [Iac+16]) are applied that might prevent the execution of parameter changes.

Figure 6.18 and Figure 6.19 present the simulation results by focusing on the fraction of unsatisfied users and the HOSR performance for the refined operator objectives – *with* and *without* the coordination functionality active. As the results for the entire network and the two cell locations show, the KPIs can be (slightly) improved towards the various directions even further with a thoughtful selection of SON functions. This is observable by comparing the green and blue coloured *dashed* lines with the *solid* ones. However, degradations are noticeable (Figure 6.19c) and the wrongfully executed objectives (the blue line of Figure 6.18c should be below the green line) is still not

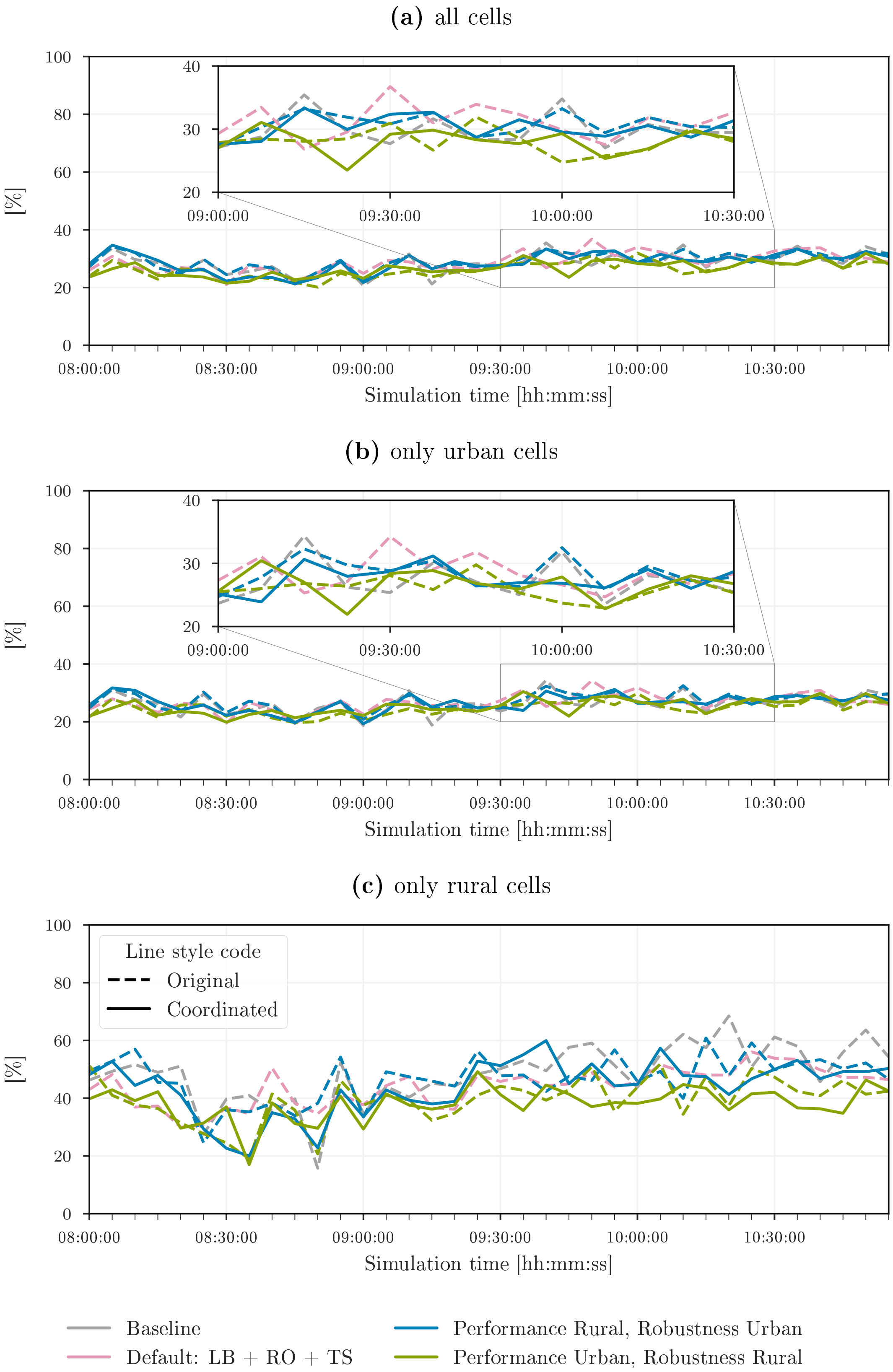


Figure 6.18: Coordinated SON operations (refinement): *unsatisfied users*

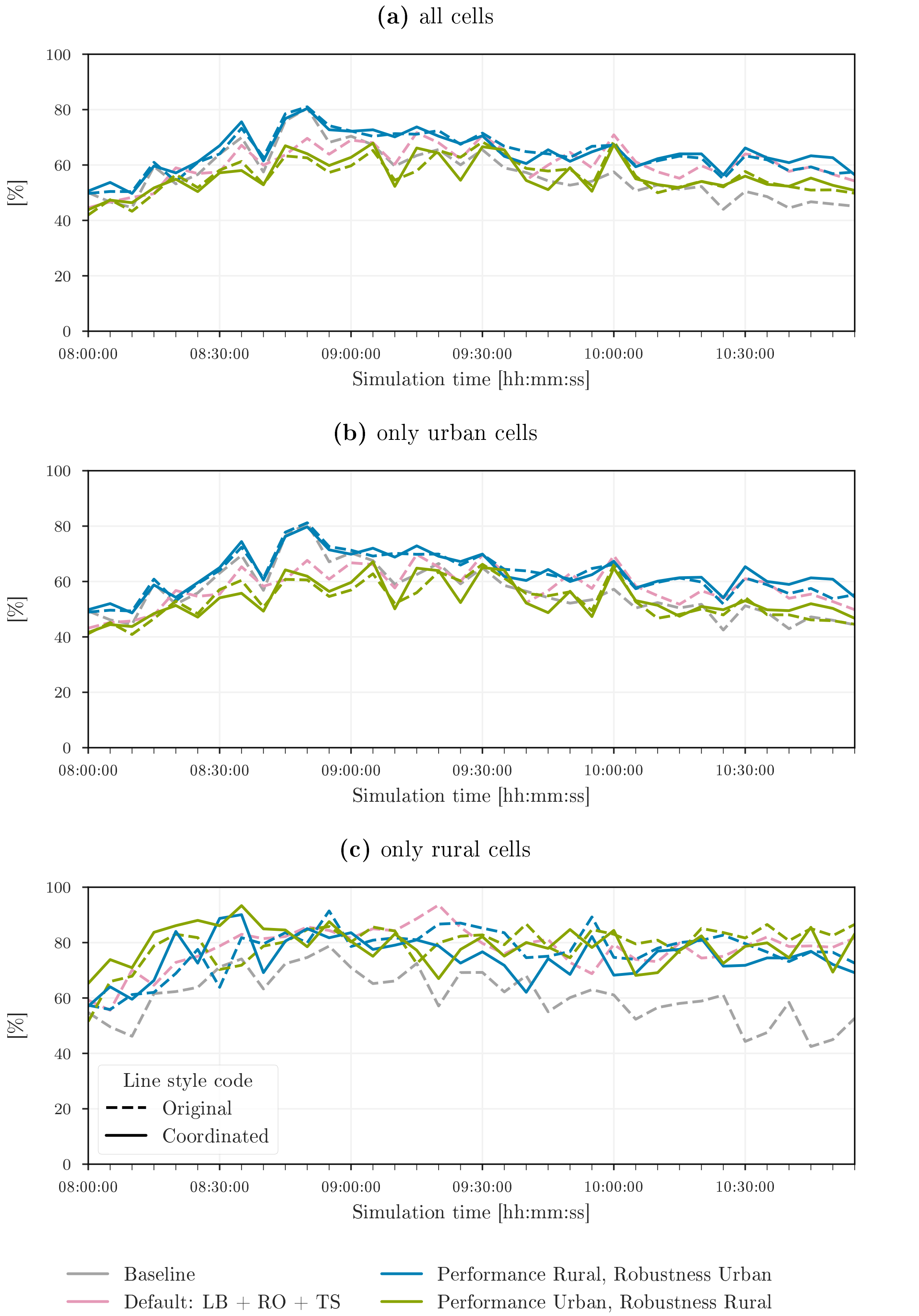


Figure 6.19: Coordinated SON operations (refinement): *handover success ratio*

rectified. This (again) is a strong indication that a learning component that adapts the decisions on what SCVs are selected over time is inevitable in such a complex cellular network. Furthermore, it also points out that an MNO needs a long-term support that helps in evaluating, assessing, and upgrading (SON) components in the system.

To conclude, what the results of section 6.3 show are that the different SON functions can be combined and used in SON management approaches. This is especially true if the SON functions tackle equal optimisation goals, such as load balancing (e.g. LB and TS). As soon as the SON functions have contradicting goals (e.g. LB and RO) the *theoretical* performance deviates from the *actual* KPI behaviour. Moreover, the insights gained can be used to further shape the SON management decisions by selecting the correct functions to improve the network performance further – but still only to some extent. The limitations are mainly due to the capabilities and availabilities of dedicated SON functions in the cellular network.

6.4 Instructions for a Mobile Network Operator

This section sums up the major scientific findings of this and the previous chapters by describing the implemented *management layer* – as initially introduced in chapter 1. Figure 6.20 shows this layer with all its developed and applied components. On top, of course, is the MNO which formulates the objectives and passes them to the management layer below that is represented by the red box in the middle. Within this management layer, three blocks are shown in blue. These blocks are the components defined by external sources: the SFPMs, coming from the vendors of the SON functions, the operator objectives and the cell classes, as mentioned, both specified by the MNO. All elements are labelled with different indices, where:

- b is the base station in the network
- c is the defined cell class
- k denotes for a specified KPI
- s is the considered SON function

Shown in orange is one integral part: the SON Objective Manager (SOM). It combines all three (external) components and selects the right SCV sets and passes them to the base stations and APs in the system. The lower grey box in Figure 6.20 indicates the heterogeneous multi-layer and multi-RAT mobile network. While others have worked on different versions of the SOM, e.g. Christoph Frenzel [Fre16] or the EU project SEMAFOUR [Hah+15b, pp. 57], the main focus was not to further investigate

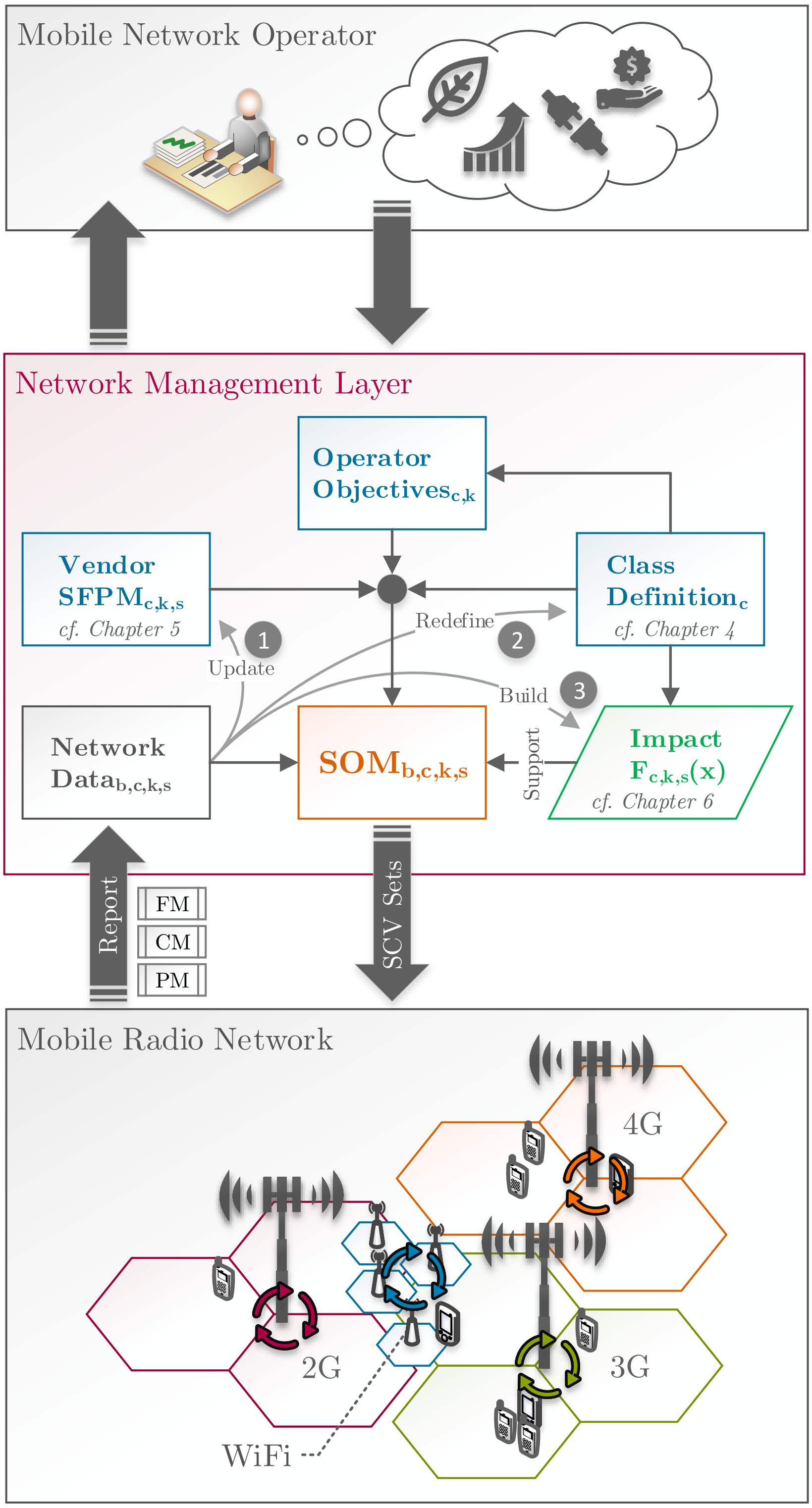


Figure 6.20: Recommendations for an MNO on how to implement a (self-organising) network management layer and where to further improve the interworking of the different blocks inside the layer

this part of the management layer. This thesis used a simplified version of the SOM and took the resulting network reports, e.g. Fault Management (FM), Configuration Management (CM) and Performance Management (PM) data (shown as a grey box in the management layer), to further analyse and (re)define the interworking of the different components. Moreover, it added more information (shown as a green box) to the interworking of the different blocks. Having taken all these factors into account, the following three recommendations to the MNO shall enable a mature (self-organising) network management:

❶ – Update the given performance models:
Vendors most likely generated the provided SFPMs by using simulations. Yet, the SON functions might perform differently in a real system. For that, a MNO should update the models by using real KPI measurements, which also helps the SOM in choosing the right SCV sets. The authors of [LSH16] have already presented an approach that incorporates different types of SFPMs. Moreover, it is most likely that the actual network performance is also changing due to the introduction of new RATs, cell densifications or changes in the data traffic demands.

❷ – Redefine the cell class definition:
It may be the case that certain classes are futile and others have to be further refined. For example, urban cells might need a much finer fragmentation due to the compound environments (smaller inter-site distances, street canyons, etc.), whereas rural cells are much easier to handle due to larger cell sizes. The collection of KPI measurements can provide clues over time for that. This also helps the MNO in defining and prioritising objectives and the SOM. This point is also tightly coupled with the recommendation just mentioned to update the SFPMs.

❸ – Build up SON impact models:
With many SON functions that run in parallel in a live network, the system has to learn the interactions of the different algorithms. The impact model (green box in Figure 6.20) will add information how certain SON functions behave and influence each other by deriving the dominating probabilities mentioned. Finally, this model can also support the SOM in its decision takings. Initial starting points might be expert knowledge or, similar to the SFPMs, simulation results.

6.5 Concluding Remarks

After evaluating the possibilities of a SON management system as well as the impact of SON functions combinations on a realistic large-scale mobile network scenario in many facets (cf. subsection 4.2.5), the following concluding remarks can be made:

- As section 6.2 shows, a managed SON function operation results in a better network performance. The alternative for an MNO would be to stick to the default SCV sets chosen by the vendors of the SON algorithms. These performance gains achieved are mainly due to the insights gained by the SFPMs, which enables a fine tuned SON operation tailored for the global network performance.

- SON functions, even in a stand-alone operation, can have a positive impact on the overall network performance. However, as scientific work has already shown (e.g. [Jan16, pp. 183]), also an adverse effect can be seen in some network conditions, due to the complex and fast changing data traffic demands.

- Multiple instances of different SON functions that run in parallel are leading to different performance results compared to single (stand-alone) SON functions (cf. subsection 6.2.1). This is the first indication of an influential behaviour of the different (radio) parameter changes executed by the various SON algorithms that are active in the mobile system.

- A KPI objective refinement per cell class is doable – but only to some extent. For a global setting (see subsection 6.2.2), the SFPMs used lead to a desired outcome by steering the performance of the whole network towards more *robustness* or *performance*. A further refined SON management system reaches its limits regarding fulfilment of KPI objectives. The main reasons here are the tremendous complexity of the large-scale simulation scenario with many (realistic) MMs and varying data traffic applications. But also the availability and capability of SON functions can play an important role. If the (refined) objectives are supposed to be executed by SON functions that have limited abilities to alter the KPIs, the performance might not be in line with the desired goals. This also proves that a long-term evaluation of the system is required to support the MNOs.

- With the results of section 6.3 in mind, different SON function combinations can have a profound impact on the overall network performance as well as on dedicated cell classes (as defined in section 4.1). This is the second indicator that the various SON functions influence each other. The analysis reveals that algorithms tackling the same optimisation goals *behave* differently and *influence* each other in disparate ways.

- Finally, as shown with the previous point, SON functions can be combined to provide means to use advanced management approaches. The combinations should incorporate a dominating probability, as proposed in [Fre16, p. 113]. With the right setting of this probability, the performance of the *theoretical* combination of two SON functions can be brought much closer towards the *actual* performance of the two SON functions that run in parallel in the mobile system. This also improves the SOM decisions by incorporating the knowledge gained and, thus, enabling a "coordinated" SON execution. This means, a profound SON coordination and real network measurements are inevitable when operating a SON-enabled system.

Chapter 7

Conclusions and Future Work

This thesis focuses on the orchestration and coordination of Self-Organising Network (SON) functions to provide means to the Mobile Network Operator (MNO) to formulate and execute dedicated Key Performance Indicator (KPI) objectives. For that, three well-known SON algorithms are used to alter the network performance, namely: the Load Balancing (LB) and Robustness Optimisation (RO) SON functions for Long Term Evolution (LTE) systems and a Traffic Steering (TS) function that shifts users between LTE and Wireless Local Area Networks (WLANs). The evaluations rely on a sophisticated, in-house developed, system-level simulation tool named Simulator for Mobile Networks (SiMoNe). With SiMoNe, various mobile radio network aspects can be modelled and investigated, but this dissertation only considers *realistic* modelling assumptions, including the user movements and behaviours (see section 7.1). To orchestrate the SON functions in a right way, a basic understanding of the impact on the realistic network topology is crucial. This is obtainable by deriving SON Function Performance Models (SFPMs) for each SON function (cf. chapter 5). With the derived SFPM and so-called cell classes, a basic Policy-Based SON Management (PBSM) approach is used, and the ability to steer a mobile network towards certain KPI directions is investigated (cf. chapter 6).

Furthermore, the investigation and the understanding of various combinations of SON functions is decisive, since different optimisation goals can influence the algorithms. Finally, with the insights gained, a network management layer could be defined and recommendations are given to the MNO how to run a SON-enabled network in a mature way. Yet, with the 5th Generation (5G) of mobile communications on the horizon, the complexity can only increase. The future of mobile radio communication also opens up a lot of new use cases that need to be studied. The sections following now address the points just mentioned individually and provide an outlook.

7.1 Realistic Mobile System Modelling

A significant emphasis is put on *realistic* modelling assumptions to conduct the system-level simulations. This includes a realistic *network topology*, a realistic *user mobility* as well as a realistic *data traffic mix*. Regarding the network topology, the so-called "Urban Hannover Scenario" is used that consists of multiple realistically planned networks, e.g. LTE cells operating at 1800 MHz or WiFi Access Points (APs) at 2400 MHz. Thomas Jansen [Jan16] and, especially, Dennis M. Rose [Ros+16a] developed major parts of the whole scenario. For a detailed description and evaluations, please consider the cited references. As for the mobility modelling, different Mobility Models (MMs) are used. A comprehensive analysis of the Handover (HO) decision points, specified by 3GPP, is done in chapter 3. Results show that there are indeed differences in the HO behaviour induced by the various MMs that build on real geographical data. The evaluations rely on a comparison using a traditional random walk MM as a reference. The differences mainly originate from the aim-oriented movements and the introduced user behaviours that mimic real actions as well as possible. The random walk MM, on the other hand, does not feature such characteristics at all. The last point addresses the data traffic modelling. Here, acclaimed approaches coming from the Next Generation Mobile Networks (NGMN) consortium are considered that account for various service types [Irm+08] (cf. Table 4.1 in subsection 4.2.1).

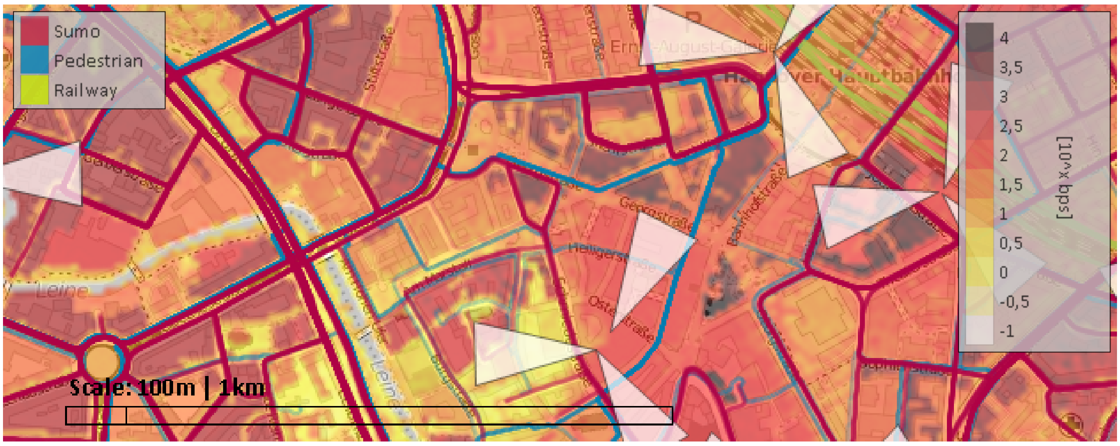


Figure 7.1: Merging of the macro- and microscopic view (cf. section 2.1)

Future work regarding the realistic network modelling is the interconnection of multiple MMs, meaning that currently each MM stands for itself. An indoor user moves inside a building for the whole simulation time; a pedestrian walks from one building entrance to another; high-speed users stay on highways; and so on. To overcome this shortcoming, and to bring the network simulation even closer towards reality, the fate of individual users might be modelled as a whole. This is achievable by simulating an indoor user first, then this user walks towards a car and uses this vehicle to reach a dedicated destination. Moreover, microscopic system-level simulations are often limited to a few hours of simulation time. Long-term evaluations are often in the vicinity of macroscopic simulations. HO events, however, can hardly be simulated with such an approach. As implied with Figure 7.1, the two views (i.e. the shown traffic map in the background and user trajectories as coloured lines) might be brought (closer) together to affect large-scale (system-level) simulations that enable a thorough evaluation of mobile radio systems. For that, the data traffic modelling and the individual user trajectories would need to match the spatial data traffic distribution – this in itself is an ambitious endeavour.

7.2 From Self-Organising to Cognitive Networks

The altering of the network performance is realised by using three SON functions. Before doing that, it is necessary to gain a deeper understanding and to get a detailed view of the actual behaviour of the SON algorithms. This is achievable by testing the functions in different network environments with changing values of the respective SON Function Configuration Parameters (SCPs), i.e. the SON Function Configuration Values (SCVs). Simulation results show that, based on the environment and the chosen SCVs, the SON functions *behave* differently. This knowledge is used in the following step to alter the network performance so that it is in line with pre-formulated MNO objectives. When considering the whole system, it is possible to steer the network. Either to higher performance, which means that the fraction of unsatisfied users is lower compared to a system without any SON functionality. This is also true when considering a network that uses default SCV settings. Alternatively, the system is steered towards a higher robustness, i.e. a better Handover Success Ratio (HOSR) performance. However, with further refined objectives, i.e. the targets are not valid for all cell locations, but only for a subset, not all goals are achievable. The main reason for that lies in the complexity of the realistic mobile network itself. With 1000 cells, two Radio Access Technologies (RATs), different cell sizes, varying traffic conditions and the presence of realistic MMs, the network management becomes too complicated for the SON functions used and the added objective intricacy. However, also the influence and the availability of SON functions plays an important role. Moreover, the combinations of multiple SON functions that run in parallel also depend on the optimisation goal of the different algorithms and, hence, have to happen with caution.

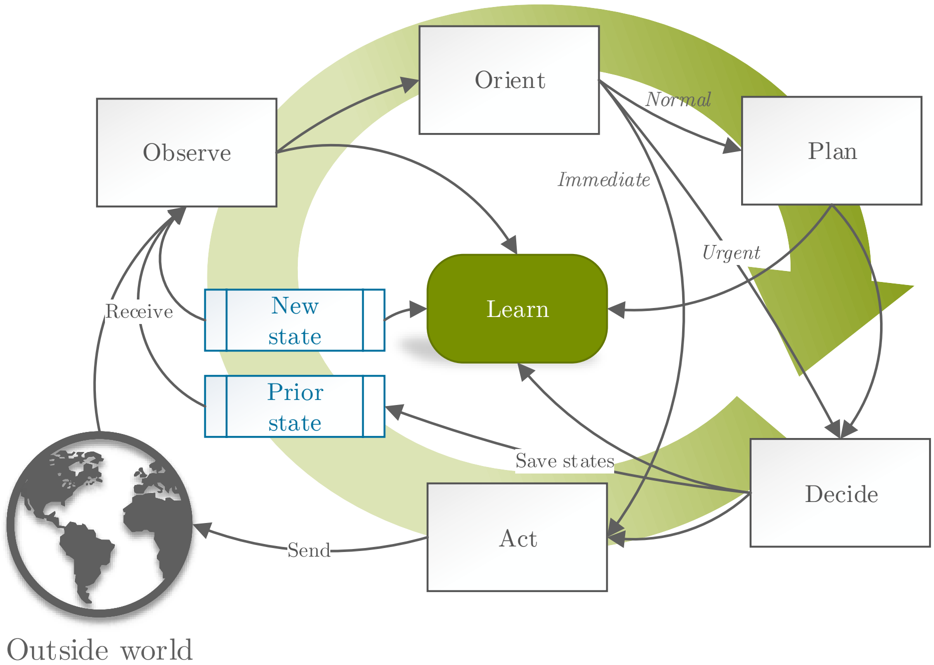


Figure 7.2: The cognitive cycle defined by [MM99]

A learning component seems to be inevitable to cope with the network complexities and changing conditions to overcome this deficiency. However, this has been out of the scope of this thesis. Learning can be seen as a cognitive component that is included in the mobile system. The authors of [MM99] introduced a so-called *cognitive cycle*. Figure 7.2 shows this cycle which consists of five steps: observe, orient, plan, decide and finally act. After that, the cognitive system stores the so-called *state* information and starts the cycle all over again. The system can build up knowledge (central green block in the middle of Figure 7.2) and change its behaviour during the run-time of the mobile system. It is already possible to inherently consider SON as some kind of *cognitive* solution. However, the independent changing of the behaviour is missing. Longer simulation times and additional components have to be implemented to realise this demeanour. Moreover, the system needs time to enable a thorough learning, which is also one of the main obstacles when trying to introduce such an approach in system-level simulations as used for this thesis. The simulated network time to collect enough state information still requires much computational power. As future work, solutions to speed up the simulations and to gather enough state information is a decisive step to evaluate complex cognitive systems. Ideally, the ability to have access to *real* network measurement data – provided by an MNO – would be of highest interest to ensure profound scientific results.

7.3 The Future of Mobile Radio Communications

Mobile radio networks evolve – and this will most likely not stop in the future. Looking at the changes from the 2nd Generation (GSM, GPRS, EDGE) (2G) to the 4th Generation (LTE, LTE-A, LTE-U) (4G) of mobile radio communications, primarily the achievable data rates increased with each step. 5G is going to address even more challenges at once. Besides further increasing the data rates, the needs for ultra-low latency requirements (for example tactile internet use cases) or massive machine type communications (such as Internet of Things (IoT) applications) arise [Pur+15]. New business models are implementable based on that, which is not only an opportunity for the MNOs but also a threat because new players will try to position themselves in the (new) markets. Eventually, this will result in a reshaping of the whole industry. Exemplary market studies and network solutions for a *Smart Factory* use case have already been presented in a master thesis[1]. These new aspects will result in new scenarios that cover a plethora of use cases as shown in Figure 7.3 [Oss+14]. Consequently, all this requires a flexible, agile and scalable network architecture, by incorporating new and eruptive concepts such as *network virtualisation* or the use of *software defined radio* components [Que+15], [Ros+16b]. But this will most likely not suffice. Additional waveform candidates, apart from the well-known OFDM techniques, might find its way into the mobile system to cope with the multitude of use cases that 5G will address [Wil+15]. This also leads to new SON – or *cognitive* – functions to solve these specific problems in the network. The authors of [Kür+15] have already presented some initial ideas.

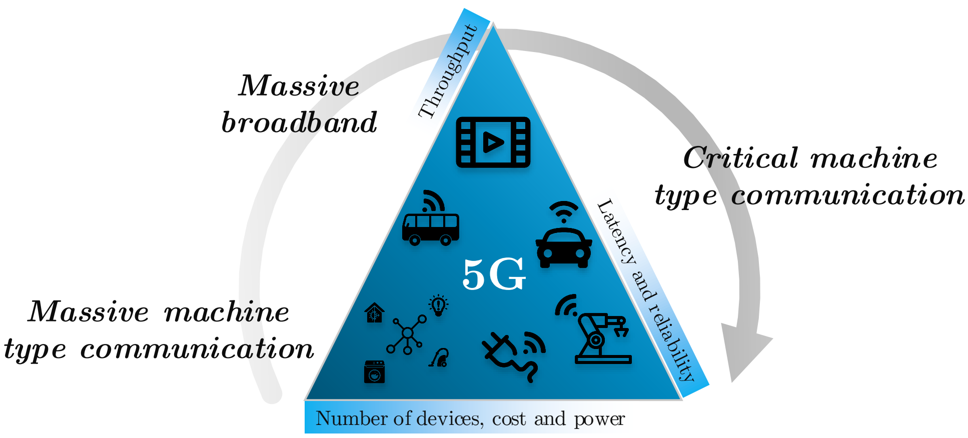


Figure 7.3: The three dimensions of the 5G requirements as of [Pur+15, p. 38]

[1] P. Becker, "Solutions for Integrated Network Management: Market Analysis, Business Models and Technical Requirements", Masterarbeit, Technische Universität Braunschweig, Institut für Nachrichtentechnik, Dipl. 16/021, 2016

To tackle these new dimensions of complexity, a self-learning and thus adapting network management system is needed. As the results from chapter 5, chapter 6, and especially chapter 3 show, realistic system modelling will also play a significant role here to assess the different management approaches. Having taken all these factors into account, this dissertation has paved the way to conduct, analyse and validate mobile radio systems of the next generation. This was done by a) empowering a high-efficient, in-house developed software solution (i.e. SiMoNe), b) improving existing multi-layer, multi-RAT network scenarios by bringing it several steps closer to reality and finally c) investigating various (self-adapting) network functions in a large-scale mobile system.

Appendix A

SON Function Configuration Values

Table A.1: LTE LB SCVs

SCV ID	Max. load [%]	SeNB load [%]	TeNB load [%]	Max. CIO [dB]	Step size CIO [dB]
1	100	90	80	6	1.0
2	100	90	80	6	0.5
3	100	90	80	3	1.0
4	100	90	80	3	0.5
5	100	80	70	6	1.0
6	100	80	70	6	0.5
7	100	80	70	3	1.0
8	100	80	70	3	0.5
9	100	70	60	6	1.0
10	100	70	60	6	0.5
11	100	70	60	3	1.0
12	100	70	60	3	0.5
13	90	80	70	6	1.0
14	90	80	70	6	0.5
15	90	80	70	3	1.0
16	90	80	70	3	0.5
17	90	70	60	6	1.0
18	90	70	60	6	0.5
19	90	70	60	3	1.0
20	90	70	60	3	0.5
21	90	60	50	6	1.0
22	90	60	50	6	0.5
23	90	60	50	3	1.0
24	90	60	50	3	0.5

Table A.2: LTE RO SCVs

SCV ID	Evaluation method	Evaluation window [sec]	Number of handover events
1	Window	30	N/A
2	Window	60	N/A
3	Window	90	N/A
4	Window	120	N/A
5	Window	150	N/A
6	Window	180	N/A
7	Window	210	N/A
8	Window	240	N/A
9	Window	270	N/A
10	Window	300	N/A
11	Events	30	10
12	Events	60	20
13	Events	90	30
14	Events	120	40
15	Events	150	50
16	Events	180	60
17	Events	210	70
18	Events	240	80
19	Events	270	90
20	Events	300	100

Table A.3: LTE/WiFi TS SCVs

SCV ID	PSON [sec]	RSS threshold step size [dB]	Load threshold low [%]	Load threshold high [%]
1	10	2.0	50	80
2	5	2.0	50	80
3	1	2.0	50	80
4	10	1.0	50	80
5	5	1.0	50	80
6	1	1.0	50	80
7	10	0.5	50	80
8	5	0.5	50	80
9	1	0.5	50	80
10	10	2.0	40	70
11	5	2.0	40	70
12	1	2.0	40	70
13	10	1.0	40	70
14	5	1.0	40	70
15	1	1.0	40	70
16	10	0.5	40	70
17	5	0.5	40	70
18	1	0.5	40	70
19	10	2.0	30	60
20	5	2.0	30	60
21	1	2.0	30	60
22	10	1.0	30	60
23	5	1.0	30	60
24	1	1.0	30	60
25	10	0.5	30	60
26	5	0.5	30	60
27	1	0.5	30	60

Appendix B

Data Traffic Types

Table B.1: Parameters for voice calls

Parameter	**Characterisation** (based on [ETS97, pp. 34])
Duration	*Exponential distribution* PDF: $f_x = \lambda x^{-\lambda x}, x \geq 0$ Parameter: $\lambda = 0.01\overline{6}$ Mean: 60 seconds
Inter-arrival time	*Poisson process* PDF: $P_\lambda(k) = \frac{\lambda^k}{k!} e^{-\lambda}, k \in \mathbb{R}^+$ Parameter: $\lambda = 120$ Mean: 120 seconds

Table B.2: Parameters for video streaming

Parameter	**Characterisation** (based on [Irm+08, p. 22])
Duration	*Exponential distribution* PDF: $f_x = \lambda x^{-\lambda x}, x \geq 0$ Parameter: $\lambda = 0.00\overline{3}$ Mean: 300 seconds
Inter-arrival time	*Poisson process* PDF: $P_\lambda(k) = \frac{\lambda^k}{k!} e^{-\lambda}, k \in \mathbb{R}^+$ Parameter: $\lambda = 300$ Mean: 300 seconds
Data request	*Truncated Pareto distribution* PDF: $f_x = \begin{cases} \frac{\alpha_k^\alpha}{x^{\alpha+1}}, k \leq x < m \\ \left(\frac{k}{m}\right)^\alpha, x \geq m \end{cases}$ Parameters: $\alpha = 1.2, k = 20, m = 270$ Mean: 100 Bytes, Maximum: 250 Bytes Subtract k from the generated random value to obtain the actual data request

Table B.3: Parameters for FTP downloads

Parameter	**Characterisation** (based on [Irm+08, p. 20])
Inter-arrival time	*Poisson process* PDF: $P_\lambda(k) = \frac{\lambda^k}{k!}e^{-\lambda}, k \in \mathbb{R}^+$ Parameter: $\lambda = 300$ Mean: 300 seconds
File size (total)	*Truncated Log-Normal distribution* PDF: $f_x = \frac{1}{\sqrt{2\pi}\sigma x}e^{\frac{-(\ln(x)-\mu)^2}{2\sigma^2}}, x > 0$ Parameters: $\sigma = 0.35, \mu = 14.45$ Mean: 2 MBytes, Maximum: 5 MBytes

Table B.4: Parameters for web browsing

Parameter	**Characterisation** (based on [Irm+08, p. 21])
Inter-arrival time	*Poisson process* PDF: $P_\lambda(k) = \frac{\lambda^k}{k!}e^{-\lambda}, k \in \mathbb{R}^+$ Parameter: $\lambda = 30$ Mean: 30 seconds
Main object size S_M	*Truncated Log-Normal distribution* PDF: $f_x = \frac{1}{\sqrt{2\pi}\sigma x}e^{\frac{-(\ln(x)-\mu)^2}{2\sigma^2}}, x > 0$ Parameters: $\sigma = 1.37, \mu = 8.37$ Mean: 10710 Bytes Minimum: 100 Bytes, Maximum: 2 MBytes
Embedded object size S_E	*Truncated Log-Normal distribution* PDF: $f_x = \frac{1}{\sqrt{2\pi}\sigma x}e^{\frac{-(\ln(x)-\mu)^2}{2\sigma^2}}, x > 0$ Parameters: $\sigma = 2.36, \mu = 6.17$ Mean: 7758 Bytes Minimum: 50 Bytes, Maximum: 2 MBytes
Number of embedded objects per page N_D	*Truncated Pareto distribution* PDF: $f_x = \begin{cases} \frac{\alpha_k^\alpha}{x^{\alpha+1}}, k \leq x < m \\ \left(\frac{k}{m}\right)^\alpha, x \geq m \end{cases}$ Parameters: $\alpha = 1.1, k = 2, m = 55$ Mean: 5.64, Maximum: 53

Appendix C

Simulation Scenarios

Table C.1: Scenario card A

Name	**Urban, Normal Mobility Profile**	
Area coordinate	Easting:	4345000 ... 4347000
	Northing:	5805500 ... 5808500
	Size:	6 km^2
RATs / Layers	LTE and WiFi / macro and small cells	
LTE macro cells	LTE 1800:	195
	TX power:	46 dBm
	Bandwidth:	10 MHz
WiFi small cells	WiFi 2400:	805
	TX power:	23 dBm
	Bandwidth:	20 MHz
Mobility	Vehicular:	1900
	Pedestrian:	3000
	Tram:	2100
	Highway:	0
	Railway:	350
	Indoor:	111
	Static:	0

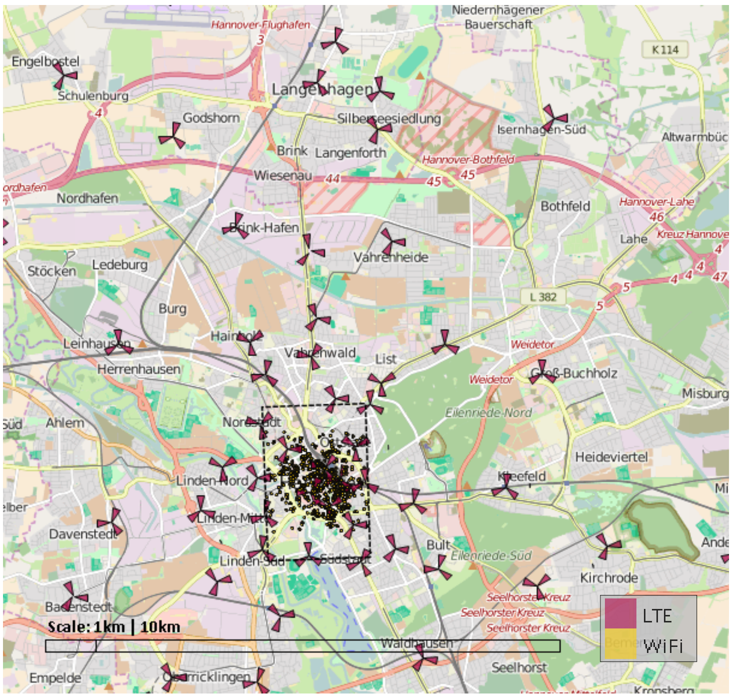


Figure C.1: Scenario A

Table C.2: Scenario card B

Name	**Rural, Normal Mobility Profile**	
Area coordinate	Easting:	4347000 . . . 4351000
	Northing:	5806500 . . . 5810500
	Size:	16 km^2
RATs / Layers	LTE / macro cells	
LTE macro cells	LTE 1800:	195
	TX power:	46 dBm
	Bandwidth:	10 MHz
WiFi small cells	N/A	
Mobility	Vehicular:	1350
	Pedestrian:	1700
	Tram:	1075
	Highway:	675
	Railway:	0
	Indoor:	0
	Static:	672

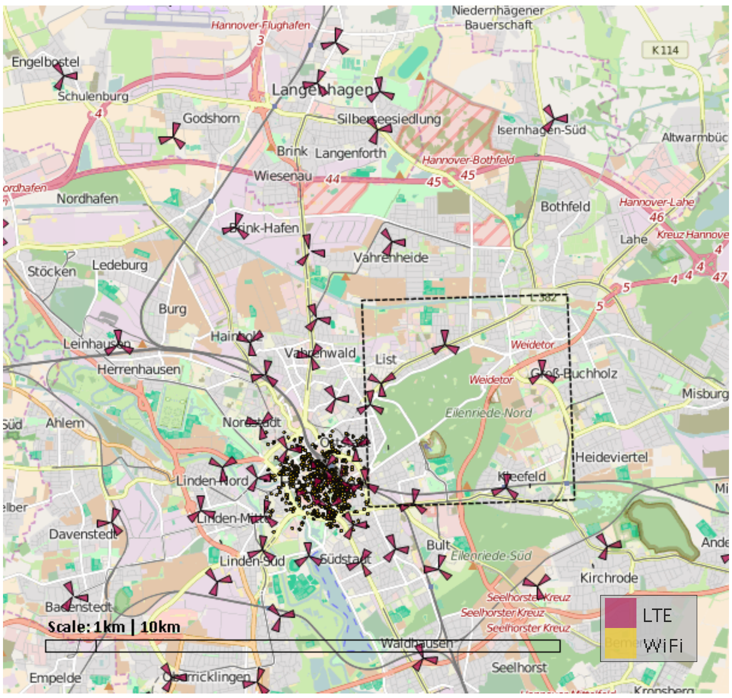


Figure C.2: Scenario B

Table C.3: Scenario card C

Name	**Rural, High-Speed Mobility Profile**	
Area coordinate	Easting:	4342500 . . . 4349500
	Northing:	5811500 . . . 5814500
	Size:	21 km^2
RATs / Layers	LTE / macro cells	
LTE macro cells	LTE 1800:	195
	TX power:	46 dBm
	Bandwidth:	10 MHz
WiFi small cells	N/A	
Mobility	Vehicular:	1900
	Pedestrian:	1500
	Tram:	1900
	Highway:	5200
	Railway:	1900
	Indoor:	0
	Static:	304

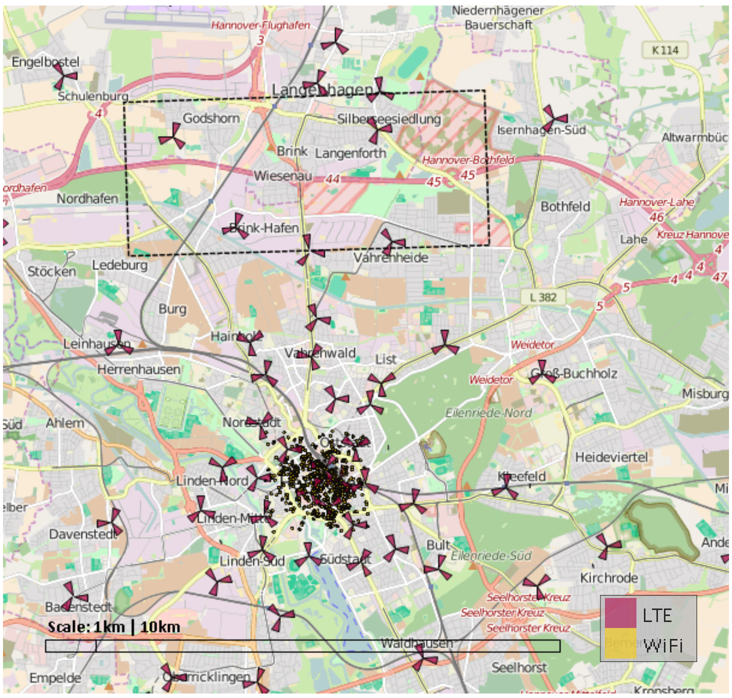


Figure C.3: Scenario C

Table C.4: Scenario card D

Name	**Hannover (10 km × 10 km)**	
Area coordinate	Easting:	4342000 . . . 4352000
	Northing:	5805000 . . . 5815000
	Size:	100 km^2
RATs / Layers	LTE and WiFi / macro and small cells	
LTE macro cells	LTE 1800:	195
	TX power:	46 dBm
	Bandwidth:	10 MHz
WiFi small cells	WiFi 2400:	805
	TX power:	23 dBm
	Bandwidth:	20 MHz
Mobility	Vehicular:	2787
	Pedestrian:	2766
	Tram:	3150
	Highway:	3150
	Railway:	1703
	Indoor:	16
	Static:	69

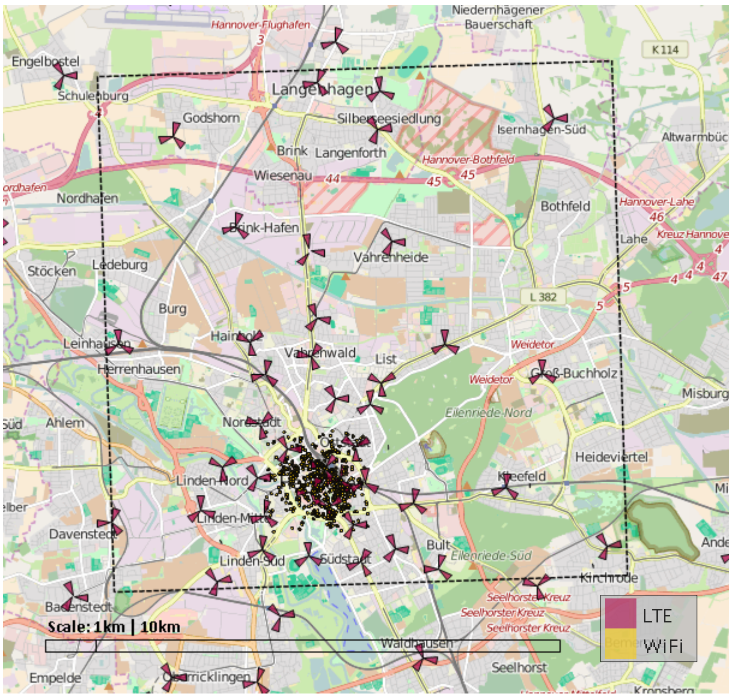


Figure C.4: Scenario D

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